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Permanent Magnet Synchronous Motors for Commercial Refrigeration: Final Report

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OAK RIDGE NATIONAL LABORATORY
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Building Technologies Research and Integration Center

PERMANENT SYNCHRONOUS MOTORS FOR COMMERCIAL REFRIGERATION: DRAFT FINAL REPORT

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CONTENTS

Page

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

Table **Page**

ACRONYMS

AC	alternating current
AMCA	Air Movement and Control Association
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BTO	Building Technologies Office, US Department of Energy
DC	direct current
DOE	US Department of Energy
EC	electronically commutated
ECM	electronically commutated motor
EERE	Energy Efficiency and Renewable Energy
M&V	measurement and verification
NCI	Navigant Consulting Inc.
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
PMS	permanent magnet synchronous
PMSM	permanent magnet synchronous motor
PSC	permanent split capacitor
PSCM	permanent split capacity motor
SP	shaded pole
SPM	shaded pole motor

ACKNOWLEDGMENTS

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ABSTRACT

This report provides background information on various fractional-horsepower electric motor technologies used for evaporator fan applications in commercial refrigeration and summarizes data from a DOE-sponsored evaporator fan motor laboratory and field demonstration project. This report also extrapolates that data to project the potential economic and environmental benefits resulting from upgrading the current installed base of commercial refrigeration evaporator fan motors to permanent magnet synchronous (PMS) motors.

Evaporator fan motors used in commercial refrigeration applications are fractional horsepower in size, responsible for moving air across the evaporator coil, and typically run at one speed. Historically, shaded-pole induction motors have been the most commonly used evaporator fan motors in commercial refrigeration equipment and beverage vending machines. These are the simplest and least expensive type of fractional-horsepower motor, with an efficiency of approximately 20%. Electronically commutated (EC) permanent magnet motors, also known as brushless DC motors, were initially commercialized in the late 1980s, and their use in commercial refrigeration applications has increased within the last 10 to 15 years because of economic incentives and regulatory requirements. State-of-the-art EC motors are approximately 66% efficient. Another induction motor type, the permanent split capacitor (PSC) motor, offers a mid-point between shaded-pole and EC motor price and efficiency levels. PSC motors are typically about 29% efficient.

A permanent magnet synchronous (PMS) AC motor that can directly use grid-supplied AC current without the need to rectify to DC has recently been commercialized. This new motor exhibits a peak efficiency of 75% and has the potential to significantly reduce the energy consumption of evaporator fan motors in commercial refrigeration equipment.

Laboratory evaluation of evaporator fan motor technologies was performed to quantify and compare the performance of shaded-pole, PSC, EC, and PMS evaporator fan motors in a controlled environment, so as to minimize the influence of external factors and anomalies. The laboratory evaluation included dynamometer testing of the fan motors and airflow testing of the motor/fan assemblies. It was found that the 6–12 W PMS motor exhibited a peak efficiency of 75% with a power factor of approximately 0.9 at a power output of 11 W. It was also found that a 38–50 W PMS motor exhibited a peak efficiency of 82% with a power factor of approximately 0.9 at a power output of 35 W.

Airflow testing of shaded-pole, PSC, EC, and PMS motor/fan assemblies was performed using an airflow test chamber, which was designed in accordance with ANSI/AMCA Standard 210-16/ASHRAE Standard 51-16, to measure the performance of the subject motor/fan assembly and to determine the incumbent display case system impedance (AMCA 2016). A family of fan curves (static pressure vs airflow rate and electrical power input vs airflow rate) was generated for the 6–12 W PMS motor/fan assemblies with 8-inch fan blades pitched from 17 to 32 degrees. A similar set of curves was generated for the 38–50 W motors paired with 10 and 12-inch blades. Various incumbent motor/fan assemblies were also tested in the laboratory airflow test chamber and their fan curves were generated.

Field evaluation of refrigerated display case evaporator fan motors was accomplished by performing side-by-side comparisons of 6–12 W PMS motors to 6–12 W shaded-pole and EC evaporator fan motors. It was found that, on average, a PMS motor consumes 79% less power and draws 82% less current than a shaded pole motor, and on average, 34% less power and 49% less current than an EC motor. In addition, the PMS motor exhibits an average power factor of approximately 0.82, which is on average 40% greater than that of existing evaporator fan motors.

Two field test sites were selected to evaluate the performance of the larger 38 to 50 W PMS evaporator fan motors in walk-in cooler/freezer applications. At each supermarket, two walk-in units were selected for investigation: one walk-in dairy cooler and one walk-in freezer. A 61% decrease in fan motor power was measured when retrofitting existing evaporator fan motors with PMS motors in the walk-in cooler. In addition, a 48% decrease in fan motor power was measured when retrofitting existing evaporator fan motors with PMS motors in the walk-in freezer.

The culmination of the field evaluation of fan motor technologies was a whole-store retrofit conducted at a supermarket. Pre- and post-retrofit measurement of evaporator fan motor power in medium- and low-temperature refrigerated display cases and walk-in coolers/freezers was performed. Overall for the whole-store retrofit, the current supplied to all monitored evaporator fan motors was reduced by 52%, the real power was reduced by 46% and the apparent power was reduced by 51% following the retrofit of the 262 evaporator fan motors that were monitored.

Based on the results of the laboratory and field evaluations of evaporator fan motors, the potential site and source energy savings associated with retrofitting the existing installed base of 6–12 W and 38–50 W commercial refrigeration evaporator fan motors with PMS fan motors was estimated. The total retrofit of all evaporator fan motors represents an annual site energy savings of 47%, and a 47% reduction in annual CO_2 emissions, compared with the baseline.

From the dynamometer test results, the power factor of the PMS motor is approximately 46% better than that of shaded-pole and EC motors. Thus, PMS fan motors, with their high power factor, will consume less current than motors with a lower power factor, resulting in reduced generation and transmission costs for utility companies.

A summary of measured evaporator fan motor efficiency and power factor determined from the dynamometer testing is given in Table 1. Table 2 gives the average reduction in power and current draw of the PMS evaporator fan motors, compared to the incumbent motors, as determined from the side-by-side display case field evaluation. Finally, Table 3 shows the average reduction in power and current draw as well as the improvement in power factor of the PMS evaporator fan motors, compared to the incumbent motors, as determined from the whole-store fan motor retrofit.

Table 1. Summary of measured evaporator fan motor efficiency and power factor

Evaporator fan motor type	Efficiency (%)	Power factor
6–12 W fan motors		
SP	26	0.64
EC	63	0.61
PMS	75	0.91
38–50 W fan motors		
SP	24	0.61
PSC	50	0.97
EC	69	0.61
PMS	82	0.92

Table 2. Performance comparison of 6–12 W incumbent and PMS evaporator fan motors from side-by-side display case field evaluations

Incumbent evaporator fan motor type	PMS evaporator fan motor performance comparison	
	Power reduction	Current draw reduction
SP	79%	82%
EC	34%	49%

Table 3. Performance comparison of 6–12 W and 38–50 W incumbent and PMS evaporator fan motors from whole-store fan motor retrofit

Incumbent evaporator fan motor type and output power	Equivalent PMS evaporator fan motor performance comparison		
	Power reduction	Current draw reduction	Power factor improvement
SP, 6–12 W	50%	60%	30%
EC, 6–12 W	38%	54%	33%
PSC, 38–50 W	49%	43%	-10%
EC, 38–50 W	47%	43%	-6%

1. INTRODUCTION

The US Department of Energy Building Technologies Office (DOE BTO) estimates that the commercial sector uses approximately 18% of all primary or source energy consumed in the United States, or 17.3 quadrillion Btu (quads) (1 quad = 10^{15} Btu) (NCI 2013). “Primary” or “source” energy refers to the sum of the energy consumed at the site (site energy) plus the energy required to extract, convert, and transmit that energy to the site, and “site” energy refers to the energy directly consumed at the site, typically measured with utility meters (Deru and Torcellini 2007). The DOE estimates that the conversion from site to source electric energy is 3.16 units of source energy per unit of site energy (DOE 2011). Therefore, the 17.3 quads of primary energy consumed by the US commercial sector equates to approximately 5.07×10^{12} kilowatt hours (kWh) of primary energy (1 Btu = 2.931×10^{-4} kWh), which in turn converts to 1.60×10^{12} kWh of site energy, valued at approximately $170 billion (EIA 2015)[2].

Of that 17.3 quads of primary energy, DOE BTO estimates that the primary energy consumption of electric motor-driven systems in the commercial sector is 4.87 quads and that the motors in central commercial refrigeration, walk-in coolers/freezers and beverage vending machines account for 6.7%, 5.7% and 3.6% of that 4.87 quads, respectively (NCI 2013). This equates to approximately 96×10^9 kWh of primary energy for central commercial refrigeration, which in turn converts to 30×10^9 kWh of site energy, valued at approximately $3.2 billion. For walk-in coolers and freezers, this equates to approximately 81×10^9 kWh of primary energy, which in turn converts to 26×10^9 kWh of site energy, valued at approximately $2.7 billion. For beverage vending machines, this equates to approximately 52×10^9 kWh of primary energy, which in turn converts to 16×10^9 kWh of site energy, valued at approximately $1.7 billion. Thus, although the evaporator fan motors used in these types of commercial refrigeration systems are only fractional horsepower in size, due to their wide proliferation and nearly constant operation, they are a significant consumer of electrical energy in the United States. Moreover, the DOE BTO reports that since refrigeration compressor motors are usually high efficiency, greater energy savings can be realized by upgrading evaporator and condenser fan motors rather than compressor motors (NCI 2013).

Although higher-efficiency motors have been increasingly used in central commercial refrigeration and beverage vending machines, the installed base of smaller 6–12 W evaporator fan motors continues to be dominated by lower-efficiency shaded-pole (SP) motors. This is also true of the installed base of 38–50 W motors used in walk-in coolers and freezers, which is dominated by lower-efficiency permanent split capacitor (PSC) motors. Over the past 10 to 15 years, the higher-efficiency electronically commutated (EC) motor has begun to penetrate the market. While EC motors are significantly more efficient than shaded pole and PSC motors, newly available permanent magnet synchronous (PMS) motors offer even greater efficiency at a comparable first cost. In addition to transforming electrical energy into mechanical energy more efficiently than EC motors, PMS motors have much higher power factors, meaning that they accept energy from the grid much more efficiently. The resulting reduced current draw means that the electric utility can reduce the amount of energy that it needs to supply to the grid.

This report provides background information on various fractional-horsepower electric motor technologies used for evaporator fan applications in commercial refrigeration and summarizes data from a DOE-sponsored evaporator fan motor laboratory and field demonstration project. This report also extrapolates that data to project the potential economic and environmental benefits resulting from upgrading the current installed base of commercial refrigeration evaporator fan motors to PMS motors.

[2] The Energy Information Administration reported that the average commercial electricity rate was 10.58 cents per kilowatt-hour during the first quarter of 2015 (EIA 2015). This price will be used throughout this report in translating kilowatt-hours used/saved to dollars at the motor level.

2. EVAPORATOR FAN MOTOR TECHNOLOGIES

Evaporator fan motors are fractional horsepower in size, responsible for moving air across the evaporator coil, and typically run at one speed. The manufacturer will match the motor size and blade to the evaporator coil to meet the expected load under most conditions. Higher-efficiency evaporator fan motors reduce energy consumption by requiring less electrical power to generate the same motor shaft output power (NCI/PNNL 2011).

Historically, shaded-pole motors have been the most commonly used evaporator fan motors in commercial refrigeration equipment, walk-in coolers and freezers, and beverage vending machines. The shaded-pole motor, a type of single-phase AC induction motor, is the simplest and least expensive type of fractional-horsepower motor. It is also the least efficient in terms of converting electrical energy into mechanical energy. The motor sizes commonly used for evaporator fans in these systems are approximately 20% efficient (NCI/PNNL 2011). Given that motor efficiency losses are released as heat, this inefficiency also increases the refrigeration load, further increasing the overall refrigeration system energy consumption (Fricke and Becker 2015).

Electronically commutated (EC) motors, also known as brushless DC motors, were originated in 1962 (Wilson and Trickey 1962) and first became widely commercialized in the late 1980s, after higher-quality rare-earth permanent magnets became more readily available (de Almeida and Greenberg 2004). The use of these premium-priced EC motors for commercial refrigeration fan applications began in earnest 10 to 15 years ago, and their use has increased because of economic incentives and regulatory requirements. Another type of induction motor, the permanent split capacitor (PSC) motor, which holds a limited share of the 6–12 W market but a more significant portion of the 38–50 W market, offers a mid-point between shaded-pole and EC motor price and efficiency levels. The DOE reports that for commercial refrigeration evaporator fan motor applications, state-of-the-art EC motors are 66% efficient and PSC motors are usually about 29% efficient (NCI/PNNL 2011).

All electric motors function as converters of electrical energy to magnetism and then to mechanical rotating motion. The operation of all electric motors is based on the interaction between a field magnet and a magnetic rotor. The electromagnetic interactions between these two magnets cause the rotor to rotate. The different types of motors result from the manner in which the rotating magnetic fields are generated.

In an induction motor, the AC current is fed into the stator coil, which creates a rotating magnetic field around the stator. This rotating magnetic field in the stator induces a current in the rotor coil, which in turn, generates a magnetic field around the rotor. The magnetic fields of the rotor and stator interact. As the magnetic field in the stator rotates, the rotor follows it and torque is generated.

Single-phase induction motors suffer from a serious shortcoming in that they only produce an interaction of two rotating magnetic fields when the rotor is rotating. Simply powering the electromagnet is not sufficient to start such a motor. One of the most significant differences among various types of single-phase induction motors is the way they handle this start-up problem (NCI/PNNL 2011).

Nearly all inexpensive fan motors are either shaded-pole or PSC induction motors. In a shaded-pole motor, a shading ring, typically a single short-circuited turn of thick copper, surrounds one side of the stator poles. Most of the magnetic flux from the stator crosses the air-gap to the rotor. However, a small portion of the flux passes through the shading ring and induces a current in the ring. The resulting magnetic flux in the ring reaches a peak after the main flux, thereby producing a rotation of the flux across the face of the stator poles. This shift in the flux across the face of the stator poles is required to start the motor. Incidentally, the side of the stator poles where the shading ring is placed dictates the direction of rotation of the motor (Hughes and Drury 2013). Because a portion of the electrical energy input is used to induce the magnetic field of the shading ring, and since the imbalance between the shaded and unshaded portions of the stator poles remains throughout operation, shaded-pole motors are inefficient.

In a PSC motor, a smaller start-up winding is present in addition to the main stator winding. The start-up winding is electrically connected in parallel with the main stator winding and in series with a capacitor, which causes a phase-shift of the current in the two windings. At startup, the interactions between the magnetic field generated by the start-up winding and that generated by the main winding create a rotating magnetic field that induces rotation of the rotor. As the motor reaches steady state, the start-up winding becomes an auxiliary winding, thereby approximating two-phase operation at the rated load point. For that reason, PSC motors are more energy efficient than their shaded-pole counterparts (NCI/PNNL 2011).

The EC motor, also known as the brushless DC or brushless permanent magnet motor, is more energy efficient than either shaded-pole or PSC motors. In the EC motor, the grid-suppled AC current is rectified to DC current. The stator is composed of individual windings. The DC current to these windings is electronically commutated (switched) by digital signals from simple rotor position sensors. As the DC current is switched to the various stator windings, a rotating magnetic field is created. This rotating magnetic field creates a torque by pulling the permanent-magnet rotor. This combination permits the motor to develop a smooth torque, regardless of speed (de Almeida and Greenberg 2004).

A permanent magnet synchronous (PMS) motor can directly use grid-supplied current without the need to rectify to DC. Synchronous motors are so named because the rotation of the motor's shaft is synchronized with the frequency of the supplied current. Previously, synchronous motors have been prohibitively expensive for commercial refrigeration evaporator fan applications because of the high cost of the electronic control circuit that is required to bring the synchronous motor up to synchronous speed. However, the PMS motor makes use of a new patented controller that is simpler and lower in cost than previous synchronous motor controllers or EC motor controllers, making the PMS motor a cost-effective alternative in the commercial refrigeration market (Flynn and Tracy 2016).

The PMS motor technology includes a split-wound stator coil as well as a motor controller with a Hall Effect sensor to detect rotor position. Upon startup, or when the Hall Effect sensor detects that the motor is not running at synchronous speed, the motor controller modifies the frequency of the AC current delivered to the stator coil to bring the motor to synchronous speed. When the frequency detected by the Hall Effect sensor matches the frequency of the input AC, the motor is running synchronously. If the motor is running synchronously, the motor controller is not needed and is switched off until either the motor falls out of sync or the motor is stopped and restarted. If the motor slows below synchronous speed, then the motor controller will control the motor timing as it does for startup. Using this method improves overall motor efficiency and the expected lifetime of the components in the circuit (Flynn and Tracy 2014).

As a result, PMS motors use less energy to provide the same power output, as compared to shaded-pole, PSC or EC motors. Since the PMS motor is a permanent magnet motor, it requires less current than an induction motor to produce the same power because no magnetizing current is necessary. Furthermore, compared with an EC motor, the PMS motor does not need to rectify AC to DC, thereby eliminating power-consuming electronics. Moreover, because they can use AC power directly from the grid, PMS motors have much higher power factors than EC motors. While the higher power factor does not mean that the PMS motor uses less power on site, it does mean that the utility is able to supply less power to the grid per unit of output power of the motor. Another inherent advantage of PMS motors is that the field coils are energized before the electronic controller, thereby protecting the electronics against power surges. Also, the elimination of the electronics from the circuit while the motor operates at synchronous speed is expected to increase the reliability and service life of PMS motors.

Finally, it should be noted that the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE) has adopted stringent energy conservation standards for some classes of commercial refrigeration equipment, including refrigerated display cases, walk-in coolers and freezers, and refrigerated beverage vending machines. These energy efficiency standards, as well as methods of test, may be found in the Code of Federal Regulations, Title 10 (Energy), Parts 429 (Certification, Compliance, and Enforcement for Consumer Products and Commercial and Industrial Equipment) and

431 (Energy Efficiency Program for Certain Commercial and Industrial Equipment)[3,4,5]. Implementation of high-efficiency evaporator fan motor technologies in commercial refrigeration equipment may be one of several methods by which manufacturers can meet the energy efficiency requirements specified in 10 CFR 431.

[3] https://www1.eere.energy.gov/buildings/appliance_standards/standards.aspx?productid=28
[4] https://www1.eere.energy.gov/buildings/appliance_standards/standards.aspx?productid=56
[5] https://www1.eere.energy.gov/buildings/appliance_standards/standards.aspx?productid=29

3. LABORATORY EVALUATION OF FAN MOTOR TECHNOLOGIES

Laboratory evaluation of evaporator fan motor technologies was performed to quantify and compare the performance of shaded-pole, PSC, EC, and PMS evaporator fan motors in a controlled environment, so as to minimize the influence of external factors and anomalies. The laboratory evaluation included dynamometer testing of the fan motors and airflow testing of the motor/fan assemblies.

Note that the 6–12 W and 38–50 W PMS motors investigated in this study have received UL (formerly Underwriters Laboratory), CSA (formerly Canadian Standards Association) and CE (Conformité Européenne) product safety certifications. UL/CSA certification was issued on 17 August 2016 under UL certification number E465664. To obtain UL/CSA certification, the 6–12 W and 38–50 W PMS motors were evaluated using the following standards: UL 1004-1 (UL 2012), UL 1004-3 (UL 2015), CSA C22.2 No. 77 (CSA 2014a), and CSA C22.2 No. 100 (CSA 2014b). Product safety testing for CE certification was performed by MET Laboratories (Baltimore, Maryland), and CE certification was issued on 20 March 2017.

3.1 DYNAMOMETER TESTING OF FAN MOTOR TECHNOLOGIES

Dynamometer testing of shaded-pole, PSC, EC, and PMS evaporator fan motors was performed to determine the power output, power factor and efficiency of the various motor technologies as the load on the motor was incrementally increased.

3.1.1 Dynamometer Test Set-up

A hysteresis brake dynamometer was used to apply a variable load on the motor being tested. The mechanical power produced by the subject motor was calculated by simultaneously measuring torque and rotational speed (RPM). An open-loop controller designed for use with the hysteresis brake dynamometer controlled the dynamometer via an internal current-regulated power supply and displayed torque, speed and mechanical power values of the motor under test. The controller was used with a personal computer to control the dynamometer and to transmit data from motor testing directly to the computer. Fig. 1 gives a schematic of the dynamometer test set-up showing the personal computer, controller, power supply, power analyzer and hysteresis brake dynamometer.

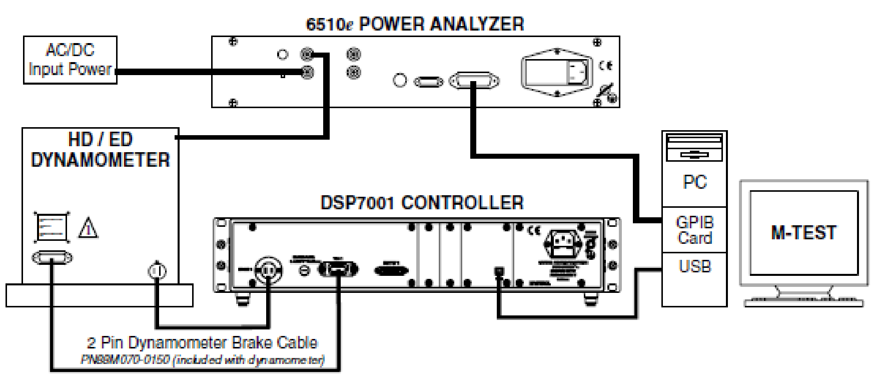

Fig. 1. Schematic of the dynamometer test set-up.

A variable power supply provided power to the motor under test via a power analyzer. The variable power supply was adjusted to provide the appropriate line voltage and frequency, for example 120 V, 60 Hz or 230 V, 60 Hz for United States applications or 230 V, 50 Hz for European applications. The power analyzer measured the voltage, current, power and power factor of the electrical power provided to the subject motor. The power analyzer also transmitted the data directly to the computer, which calculated motor efficiency as the mechanical power output divided by the electrical power input. A photograph of the dynamometer test set-up showing a display case evaporator fan motor mounted in the motor stand and coupled to the hysteresis brake dynamometer is given in Fig. 2.

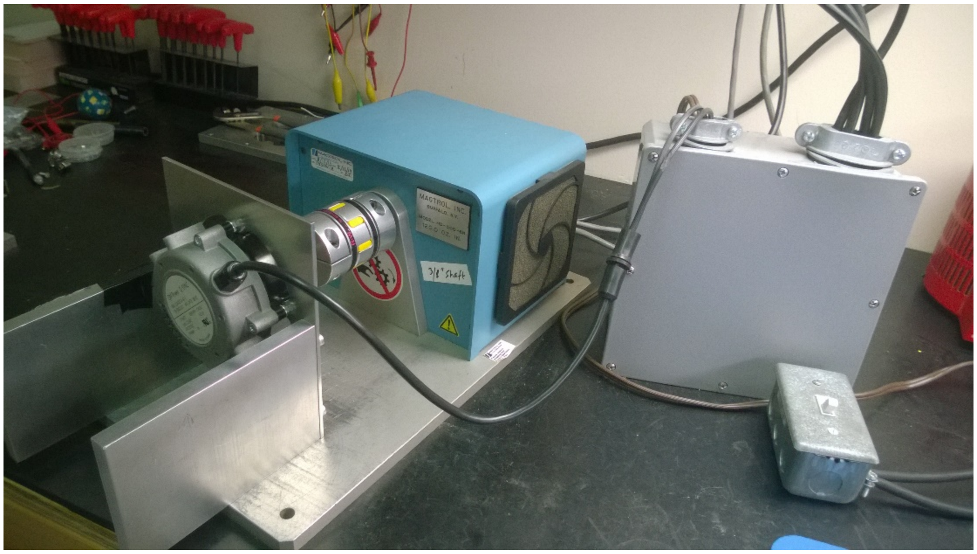

Fig. 2. Photograph of dynamometer test set-up showing a display case evaporator fan motor coupled to the hysteresis brake dynamometer.

Measured quantities in the dynamometer testing of fan motors included torque, rotational speed (RPM), and mechanical power output of the motor under test as well as voltage, current, power input and power factor of the electrical power provided to the subject motor. Fan motor efficiency was then calculated from the measured data. Table 4 lists the specifications of the instrumentation used in the dynamometer testing of fan motors.

Table 4. Instrumentation specifications for the dynamometer test

Instrument	Measured quantity	Instrument range	Accuracy
Magtrol Hysteresis Brake Dynamometer HD-500-6N	Fan motor torque, rotational speed, and mechanical power	Torque: 0 to 850 mN-m Speed: 0 to 25,000 RPM Power: 0 to 400 W	MIL-STD-45662A ANSI/NCSL Z540-1-1994
Magtrol Dynamometer Controller Model DSP7001-1-0	Fan motor torque, rotational speed, and mechanical power	Torque: 0 to 850 mN-m Speed: 0 to 25,000 RPM Power: 0 to 400 W	MIL-STD-45662A ANSI/NCSL Z540-1-1994
California Instruments Variable Power Supply 2001RP-OP1	Frequency Voltage Power	Input Frequency: 47 to 400 Hz Input Voltage: 115 VAC Input Power: 2650 W	Output Frequency: 16 to 5000 Hz Output Voltage: 0 to 300 VAC Output Power: 0 to 2000 VA
Magtrol Power Analyzer 6510e	Fan motor electrical power, current, voltage and power factor	Power: 0 to 12,000 W Current: 1 to 20 A Voltage: 30 to 600 V	Power: 0.4% Current: 0.5% Voltage: 1.6%

3.1.2 Dynamometer Results and Discussion

3.1.2.1 6–12 W Evaporator Fan Motors

Fig. 3 through Fig. 7 show sample plots of fan motor efficiency and power factor for various 6–12 W shaded-pole, EC, and PMS evaporator fan motors. Fig. 3 shows the fan motor efficiency and power factor for a 6–12 W PMS motor. This 6–12 W PMS motor exhibits a peak efficiency of 75% with a power factor of approximately 0.9 at a power output of 11 W. Fig. 4 through Fig. 6 give the fan motor efficiency and power factor for three 6–12 W EC motors from different manufactures. For comparison, these figures also show the fan motor efficiency and power factor for the same 6–12 W PMS motor shown in Fig. 3. The peak efficiency of these EC motors ranges from about 62% to 67% with power factors ranging from 0.58 to 0.66, at a power output of 10 to 14 W. Fig. 7 gives the fan motor efficiency and power factor for a 6–12 W shaded pole motor. For comparison, this figure also shows the fan motor efficiency and power factor for the same 6–12 W PMS motor shown in Fig. 3. The peak efficiency of this shaded pole motor is 27% with a power factor of 0.66 at a power output of 13 W.

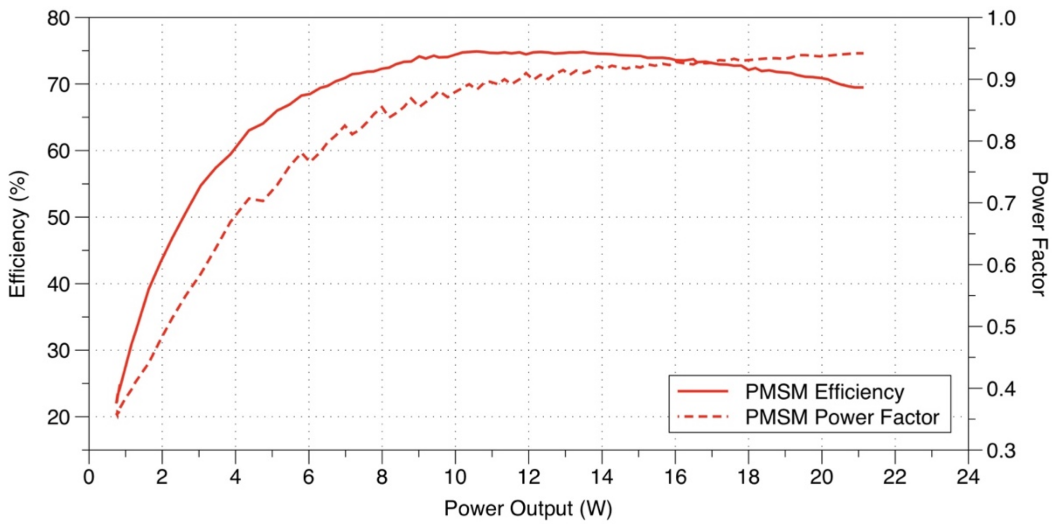

Fig. 3. Fan motor efficiency and power factor for a 6–12 W PMS motor.

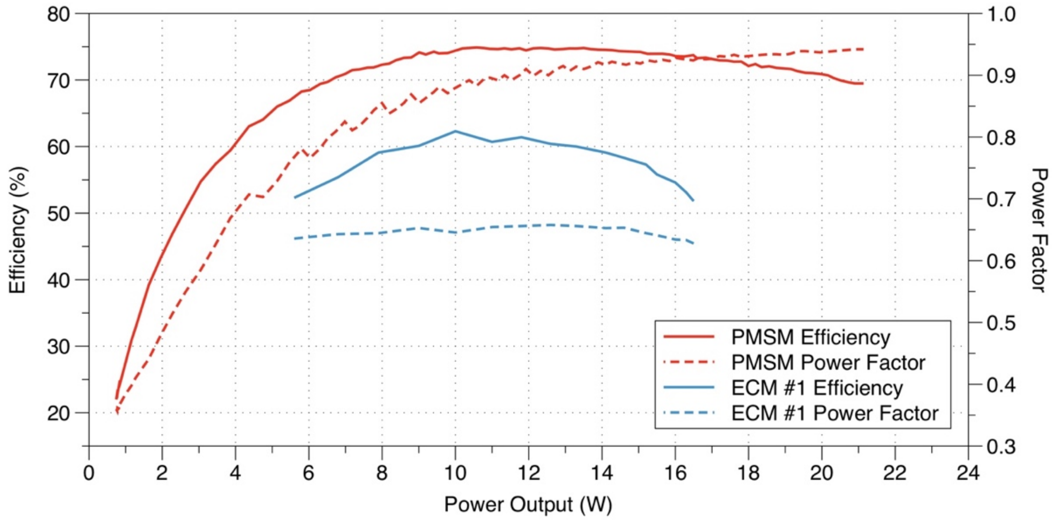

Fig. 4. Fan motor efficiency and power factor for a 6–12 W EC motor (ECM #1) and a 6–12 W PMS motor.

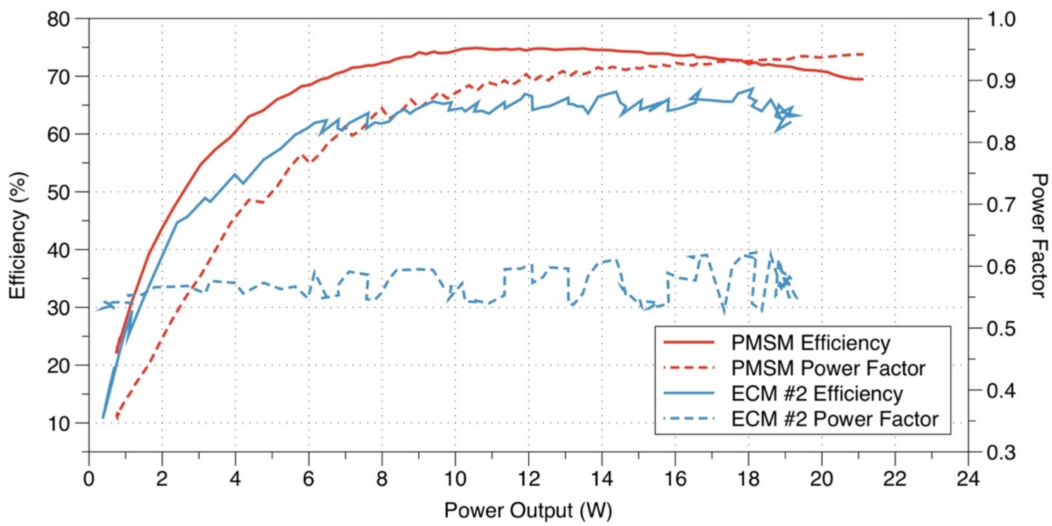

Fig. 5. Fan motor efficiency and power factor for a 6–12 W EC motor (ECM #2) and a 6–12 W PMS motor.

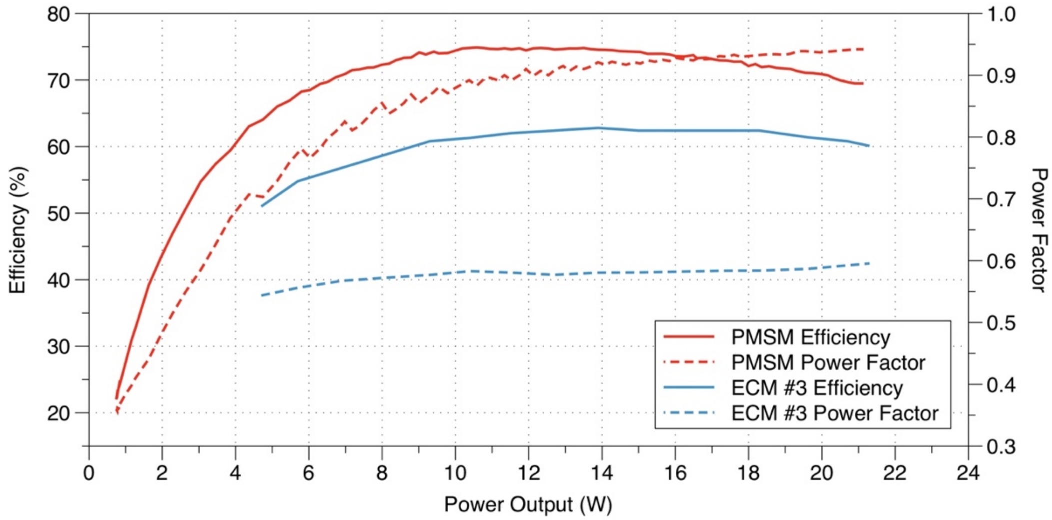

Fig. 6. Fan motor efficiency and power factor for a 6–12 W EC motor (ECM #3) and a 6–12 W PMS motor.

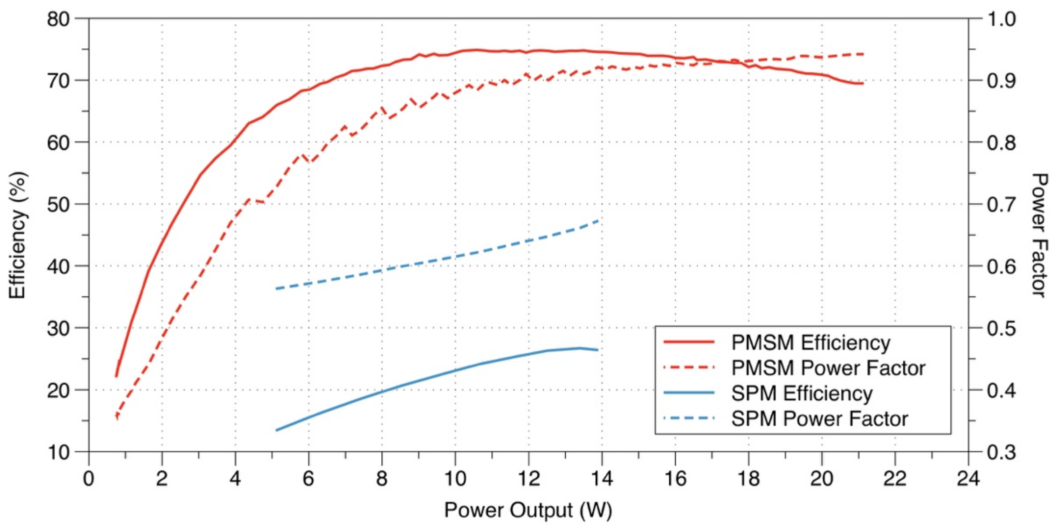

Fig. 7. Fan motor efficiency and power factor for a 6–12 W SP motor and a 6–12 W PMS motor.

A summary of the display case evaporator fan motor efficiency and power factor determined from the dynamometer testing described above is provided below in Table 5. The efficiency and power factor data presented in the table corresponds to a motor output power of 12 W.

Table 5. Efficiency and power factor for several 6–12 W evaporator fan motors

Motor type	Input power (W)	Output power (W)	Efficiency (%)	Power factor
PMS	16.1	12.0	74.6	0.91
EC #1	19.6	12.0	61.2	0.66
EC #2	18.0	12.0	66.7	0.60
EC #3	19.3	12.0	62.2	0.58
SP	46.7	12.0	25.7	0.64

3.1.2.2 38–50 W Evaporator Fan Motors

Fig. 8 through Fig. 15 show sample plots of fan motor efficiency and power factor for various 38–50 W shaded-pole, PSC, EC, and PMS evaporator fan motors. Fig. 8 shows the fan motor efficiency and power factor for a 38–50 W PMS motor. This 38–50 W PMS motor exhibits a peak efficiency of 82% with a power factor of approximately 0.9 at a power output of 35 W. Fig. 9 through Fig. 13 give the fan motor efficiency and power factor for five 38–50 W EC motors from different manufacturers. For comparison, these figures also show the fan motor efficiency and power factor for the same 38–50 W PMS motor shown in Fig. 8. The peak efficiency of these EC motors ranges from about 64% to 73% with power factors ranging from 0.51 to 0.67, at a power output of 22 to 56 W.

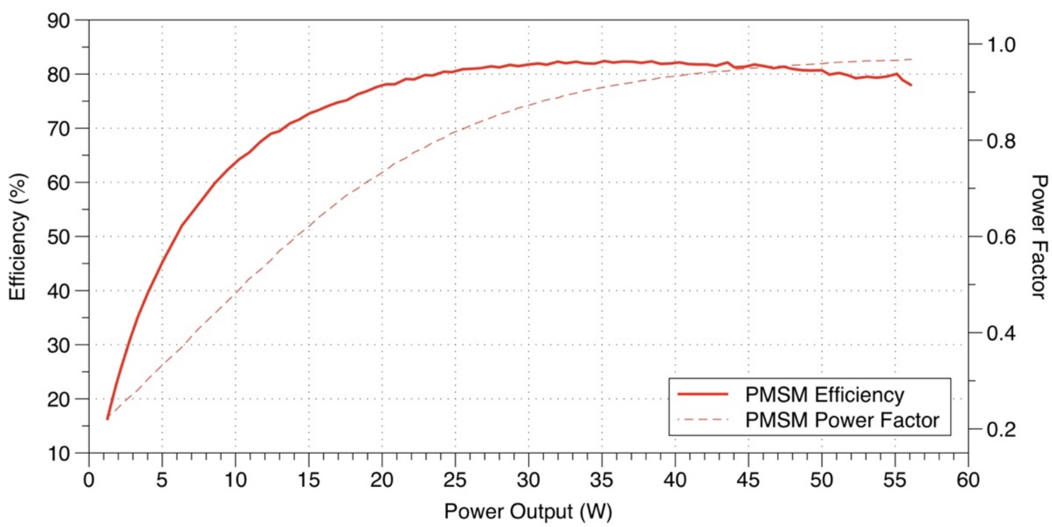

Fig. 8. Fan motor efficiency and power factor for a 38–50 W PMS motor.

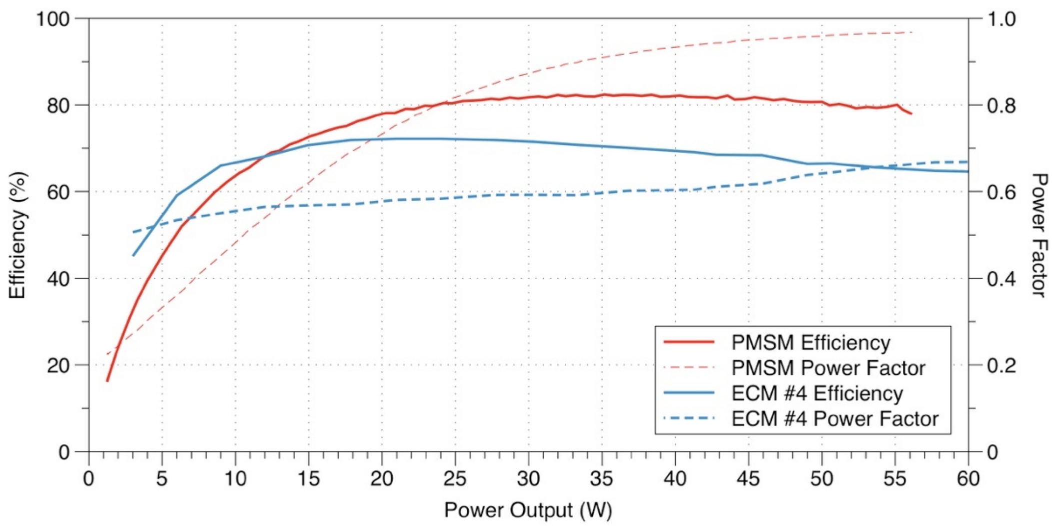

Fig. 9. Fan motor efficiency and power factor for a 38–50 W EC motor (ECM #4) and a 38–50 W PMS motor.

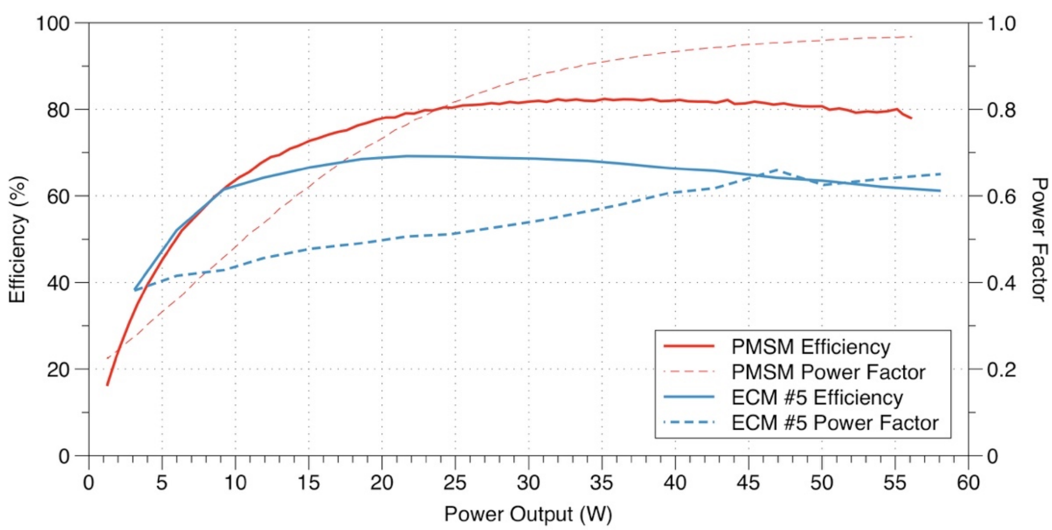

Fig. 10. Fan motor efficiency and power factor for a 38–50 W EC motor (ECM #5) and a 38–50 W PMS motor.

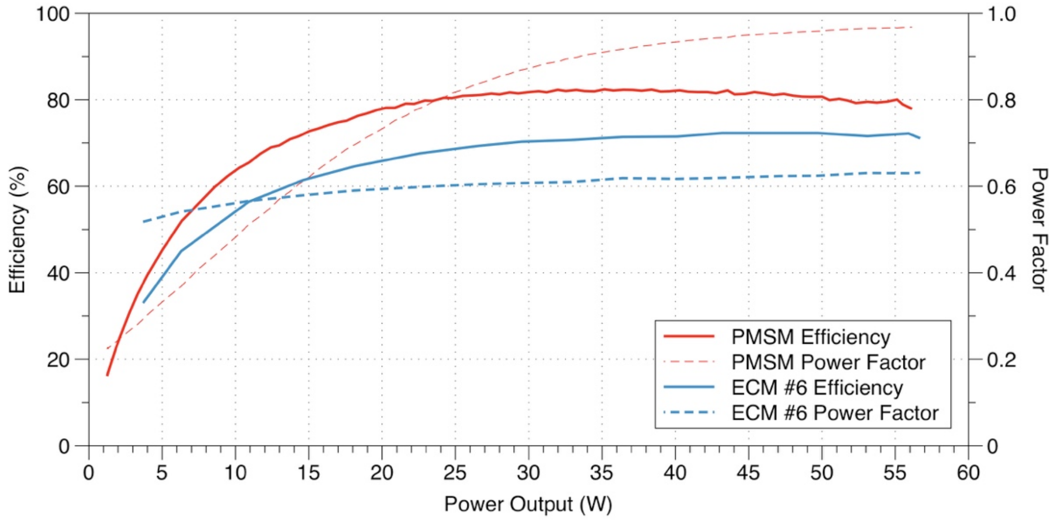

Fig. 11. Fan motor efficiency and power factor for a 38–50 W EC motor (ECM #6) and a 38–50 W PMS motor.

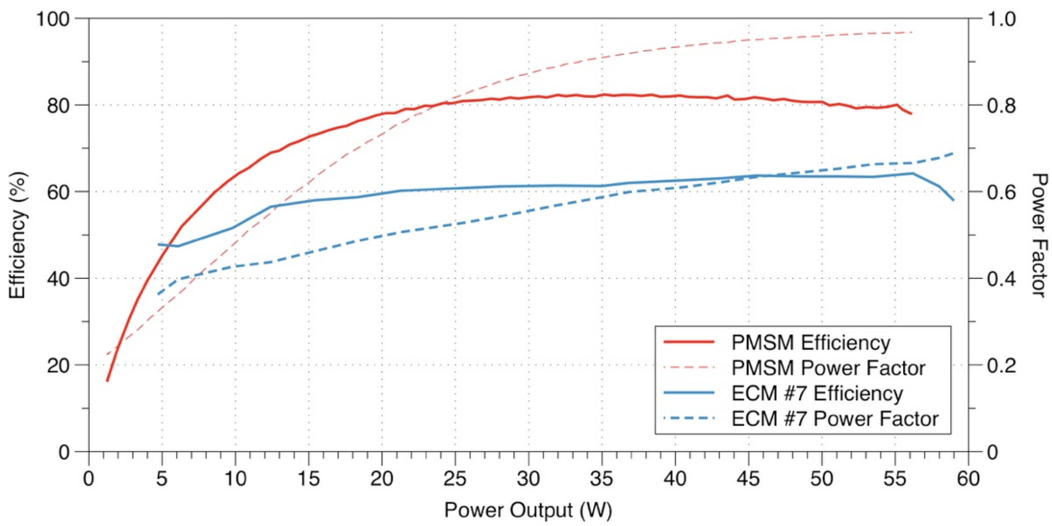

Fig. 12. Fan motor efficiency and power factor for a 38–50 W EC motor (ECM #7) and a 38–50 W PMS motor.

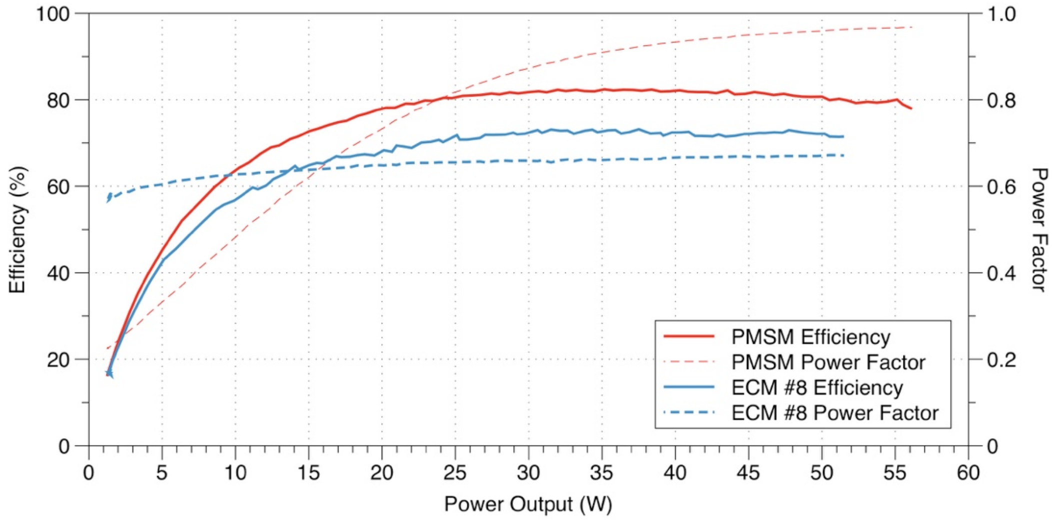

Fig. 13. Fan motor efficiency and power factor for a 38–50 W EC motor (ECM #8) and a 38–50 W PMS motor.

Fig. 14 gives the fan motor efficiency and power factor for a 38–50 W PSC motor. For comparison, this figure also shows the fan motor efficiency and power factor for the same 38–50 W PMS motor shown in Fig. 8. The peak efficiency of this PSC motor is 50% with a power factor of 0.98 at a power output of 40 W.

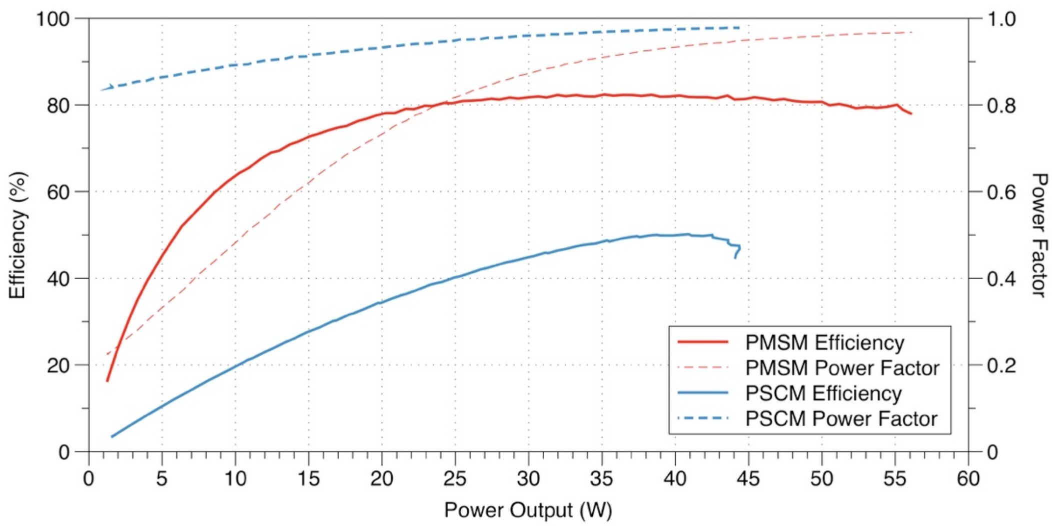

Fig. 14. Fan motor efficiency and power factor for a 38–50 W PSC motor and a 38–50 W PMS motor.

Finally, Fig. 15 gives the fan motor efficiency and power factor for a 38–50 W SP motor. For comparison, this figure also shows the fan motor efficiency and power factor for the same 38–50 W PMS motor shown in Fig. 8. The peak efficiency of this SP motor is 27% with a power factor of 0.64 at a power output of 47 W.

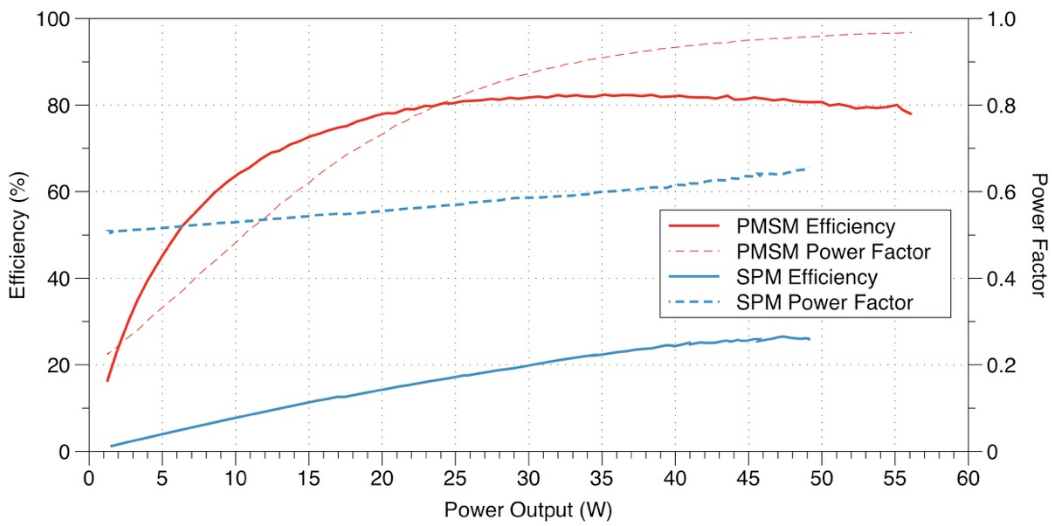

Fig. 15. Fan motor efficiency and power factor for a 38–50 W SP motor and a 38–50 W PMS motor.

A summary of the walk-in cooler/freezer evaporator fan motor efficiencies and power factors determined from the dynamometer testing described above is provided below in Table 6. The efficiency and power factor data presented in the table corresponds to a motor output power of 38 W.

Table 6. Efficiency and power factor for 38–50 W evaporator fan motors

Motor type	Input power (W)	Output power (W)	Efficiency (%)	Power factor
PMS	46.2	38	82.2	0.92
EC #4	54.4	38	69.8	0.60
EC #5	56.8	38	66.9	0.59
EC #6	53.2	38	71.4	0.62
EC #7	61.1	38	62.2	0.60
EC #8	52.4	38	72.6	0.66
PSC	76.5	38	49.7	0.97
SP	160.3	38	23.7	0.61

3.2 AIRFLOW TESTING OF FAN MOTOR TECHNOLOGIES

Since refrigeration effect depends upon airflow rate, an effort was made to match the airflow rate of the incumbent motor/fan assembly during the installation of PMS fan motors at each test site, by using appropriately pitched fan blades on the PMS motors. This is a significant issue when evaluating energy savings, because the energy usage of a fan motor depends upon how much air it is moving.

Different fan motor rotational speeds have implications for airflow rate. PMS motors are designed to run at 1800 RPM on a 60 Hz AC power supply. Typically, the incumbent evaporator fan motors were found to operate at approximately 1550 RPM. Given the faster rotational speed of the PMS motor, the use of a slightly lower pitched blade on the PMS motor, operating at 1800 RPM, gives a comparable airflow rate to that of the incumbent motor/fan assembly operating at 1550 RPM.

3.2.1 Airflow Test Set-up

Airflow testing of shaded-pole, PSC, EC, and PMS motor/fan assemblies was performed using an airflow test chamber, which was designed in accordance with ANSI/AMCA Standard 210-16/ASHRAE Standard 51-16, to measure the performance of the subject motor/fan assembly and to determine the incumbent display case system impedance (AMCA 2016). The chamber was designed with multiple nozzles to cover the full airflow range of the design. The chamber was constructed with pressure taps on each side of the nozzle plate to measure the differential pressure across the nozzle plate. The nozzles were calibrated to give airflow rate as a function of the measured differential pressure. Pressure taps near the front end of the chamber were used to measure the static pressure of the motor/fan assembly under test, which was measured as the differential pressure between the chamber and atmospheric pressure. This static pressure measurement was also used as an indicator of the incumbent display case system impedance. A variable speed auxiliary fan at the exit of the airflow test chamber was used to control the static pressure at the entrance of the chamber. A blast gate, which was located at the end of the chamber and before the auxiliary fan, acted as a sliding gate valve that was used in conjunction with the variable speed auxiliary fan to fine tune the static pressure at the entrance of the chamber. A schematic of the airflow test set-up showing the motor/fan assembly under test, as well as the static pressure taps, flow straighteners, nozzle plate, differential pressure taps, and the variable speed auxiliary fan is shown in Fig. 16.

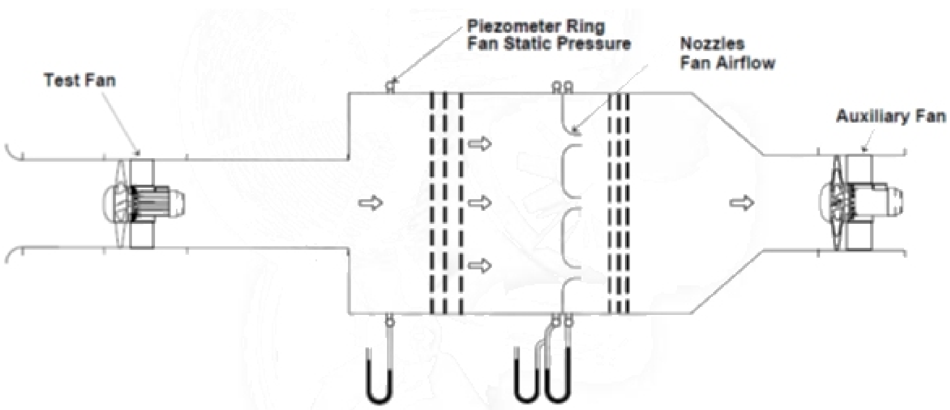

Fig. 16. Schematic of the airflow test set-up.

A variable power supply provided power to the motor/fan assembly under test via a power analyzer. The variable power supply was adjusted to provide the appropriate line voltage and frequency, for example 120 V, 60 Hz or 230 V, 60 Hz for United States applications or 230 V, 50 Hz for European applications. The power analyzer measured the voltage, current and power of the electrical power provided to the subject motor/fan assembly. A variable frequency drive was used to control the speed of the auxiliary fan at the exit of the airflow test chamber to achieve the desired static pressure reading at the inlet to the airflow test chamber. A handheld temperature and humidity meter was used to measure the air temperature and humidity at the inlet to the airflow test chamber, which was used to calculate the inlet air density. A remote optical sensor and panel tachometer were used to measure motor/fan assembly rotational speed.

A photograph of the airflow test set-up showing a display case evaporator motor/fan assembly mounted at the inlet to the airflow test chamber is given in Fig. 17. Also visible in this photograph are the static pressure gauge display, differential pressure gauge display, variable power supply, power analyzer, optical sensor, panel tachometer, and variable frequency drive used to control the auxiliary fan.

Fig. 17. Photograph of the airflow test set-up showing a display case evaporator motor/fan assembly mounted at the inlet to the airflow test chamber.

Measured quantities in the airflow testing of motor/fan assemblies included airflow rate, static pressure at the front of the airflow test chamber, differential pressure across the orifice plate of the airflow test chamber, laboratory air temperature and humidity, as well as voltage, current, and electrical power input of the electrical power provided to the subject motor/fan assembly and rotational speed (RPM) of the subject motor/fan assembly. Table 7 lists the specifications of the instrumentation used in the airflow testing of motor/fan assemblies.

This airflow test set-up was used to generate fan curves (static pressure vs airflow rate and electrical power input vs airflow rate) for the various shaded-pole, PSC, EC, and PMS motor/fan assemblies. This was accomplished with the subject motor/fan assembly mounted at the front of the airflow test chamber while the speed of the variable speed auxiliary fan and the blast gate were adjusted to achieve the desired static pressure. The differential pressure across the orifice plate of the airflow chamber was then recorded and used to determine the airflow rate via the orifice calibration curves. The electrical power input to the subject motor/fan assembly was also recorded along with motor/fan assembly rotational speed, and inlet air temperature and humidity to calculate air density. Plots of static pressure vs airflow rate and electrical power input versus airflow rate for the various shaded-pole, PSC, EC, and PMS motor/fan assemblies were then generated.

Table 7. Instrumentation specification for the airflow test set-up

Instrument	Measured quantity	Instrument range	Accuracy
Airflow Measurement Systems, Airflow Test Chamber, 5000 CFM	Air flow rate	0 to 5000CFM	ANSI/AMCA Standard 210-16/ASHRAE Standard 51-16
Setra Static Pressure Gauge, Model 2671	Static air pressure	-1.0 in water column to 1.0 in water column	3%
Setra Differential Pressure Gauge, Model 2671	Differential air pressure across orifice plate	-2.5 in water column to 2.5 in water column	3%
Center 317 Temperature and Humidity Meter	Air Temperature Humidity	Temperature: -4°F to 140°F Humidity: 0 to 99% RH	Air Temperature: 1.6% Humidity: 2.5%
California Instruments Variable Power Supply 2001RP-OP1	Frequency Voltage Power	Input Frequency: 47 to 400 Hz Input Voltage: 115VAC Input Power: 2650 W	Output Frequency: 16 to 5000 Hz Output Voltage: 0 to 300 VAC Output Power: 0 to 2000 VA
Voltech Single Phase Power Analyzer PM100	Fan motor power, current, and voltage	Power: 0 to 1,999 GW Current: 20mA to 20 A Voltage: 2 to 1000 V	Power: 0.2% Current: 0.1% Voltage: 0.1%
Monarch Remote Optical Sensor ROS-P	Rotational speed (RPM),	Rotational speed (RPM):	1 RPM
Monarch Panel Tachometer ACT-1B	Rotational speed (RPM),	Rotational speed (RPM): 5 to 99,999 RPM	1 RPM
Yaskawa AC Drive V1000	Frequency Voltage	Frequency: 2 to 15 kHz Voltage: 200 to 240 v	Frequency: 5% Voltage: 15%

3.2.2 Airflow Results and Discussion

3.2.2.1 Airflow Performance of 6–12 W PMS Evaporator Fan Motors

Fig. 18 shows static pressure and input power versus airflow rate for a 6–12 W PMS evaporator fan motor with 17° to 24° pitched 8-in. fan blades. In all of the airflow plots, the solid lines represent static pressure versus airflow rate while the dashed lines represent input power versus airflow rate. In Fig. 18, at a static pressure of 0.3 in. H_2O, the airflow rate was 63 CFM and the input power was 11.2 W for a 17° pitched fan blade, while the airflow rate was 110 CFM and the input power was 16.3 W for a 24° pitched fan blade. At a static pressure of 0.0 in. H_2O, the airflow rate was 216 CFM and the input power was 6.0 W for a 17° pitched fan blade, while the airflow rate was 305 CFM and the input power was 9.5 W for a 24° pitched fan blade. From the field measurements in Section 4, it was found that the 6–12 W motors in display case applications typically operate at a static pressure between 0.1 and 0.2 inches of water.

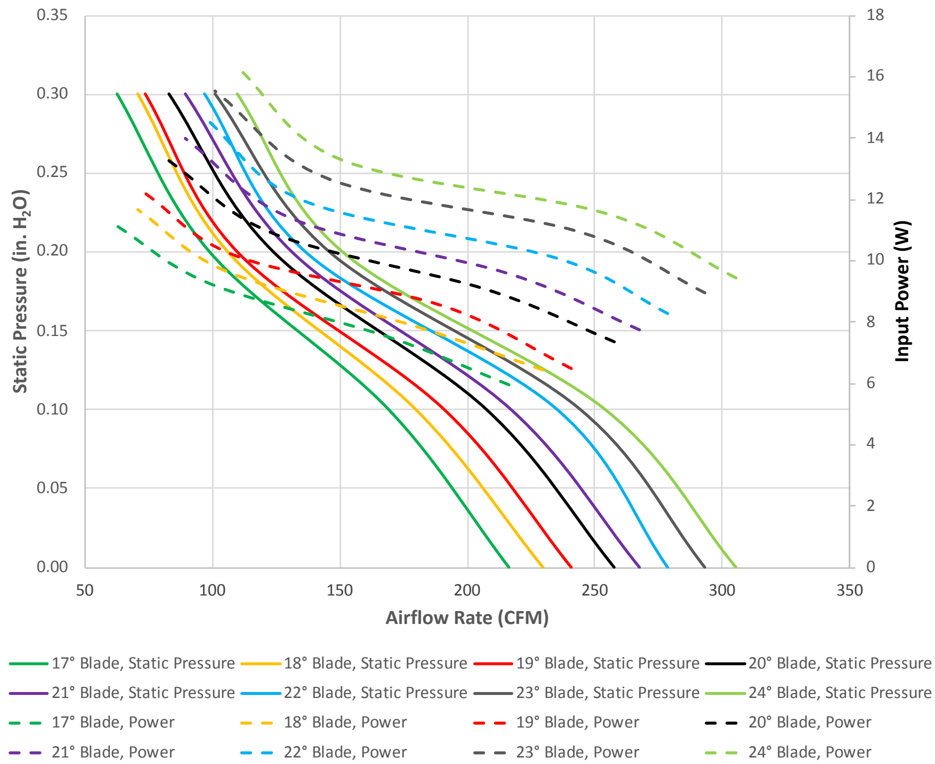

Fig. 18. Static pressure and input power versus airflow rate for a 6–12 W PMS evaporator fan motor with 8-in. fan blades pitched from 17° to 24°.

Fig. 19 shows static pressure and input power versus airflow rate for a 6–12 W PMS evaporator fan motor with 25° to 32° pitched 8-in. fan blades. At a static pressure of 0.3 in. H_2O, the airflow rate was 120 CFM and the input power was 17.2 W for a 25° pitched fan blade, while the airflow rate was 149 CFM and the input power was 24.6 W for a 32° pitched fan blade. At a static pressure of 0.0 in. H_2O, the airflow rate was 320 CFM and the input power was 10.1 W for a 25° pitched fan blade, while the airflow rate was 403 CFM and the input power was 16.5 W for a 32° pitched fan blade.

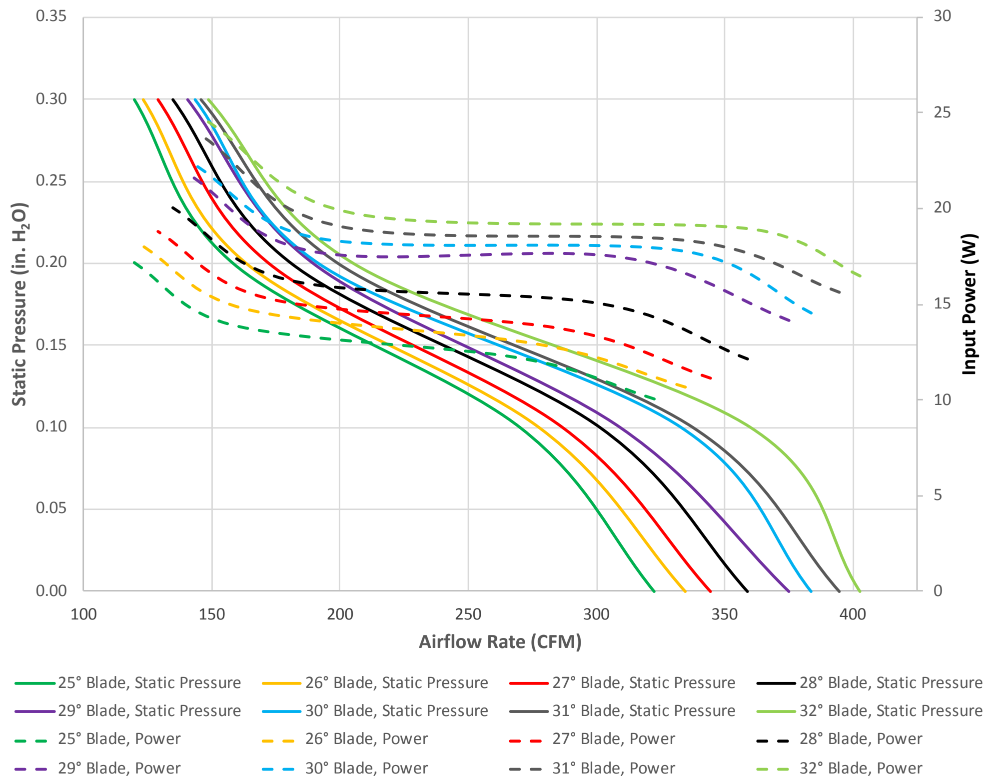

Fig. 19. Static pressure and input power versus airflow rate for a 6–12 W PMS evaporator fan motor with 8-in. fan blades pitched from 25° to 32°.

3.2.2.2 Airflow Performance of 38–50 W PMS Evaporator Fan Motors

Similar airflow curves were generated for the 38–50 W PMS walk-in motors, with both 10- and 12-inch diameter blades. From the field measurements in Section 4, it was found that the static pressures are slightly higher in walk-in applications compared to display case applications.

Fig. 20 shows static pressure and input power versus airflow rate for a 38–50 W PMS evaporator fan motor with 20° to 28° pitched 10-in. fan blades. At a static pressure of 0.3 in. H_2O, the airflow rate was 187 CFM and the input power was 25 W for a 20° pitched fan blade, while the airflow rate was 306 CFM and the input power was 41.8 W for a 28° pitched fan blade. At a static pressure of 0.0 in. H_2O, the airflow rate was 406 CFM and the input power was 19.1 W for a 20° pitched fan blade, while the airflow rate was 586 CFM and the input power was 36.0 W for a 28° pitched fan blade.

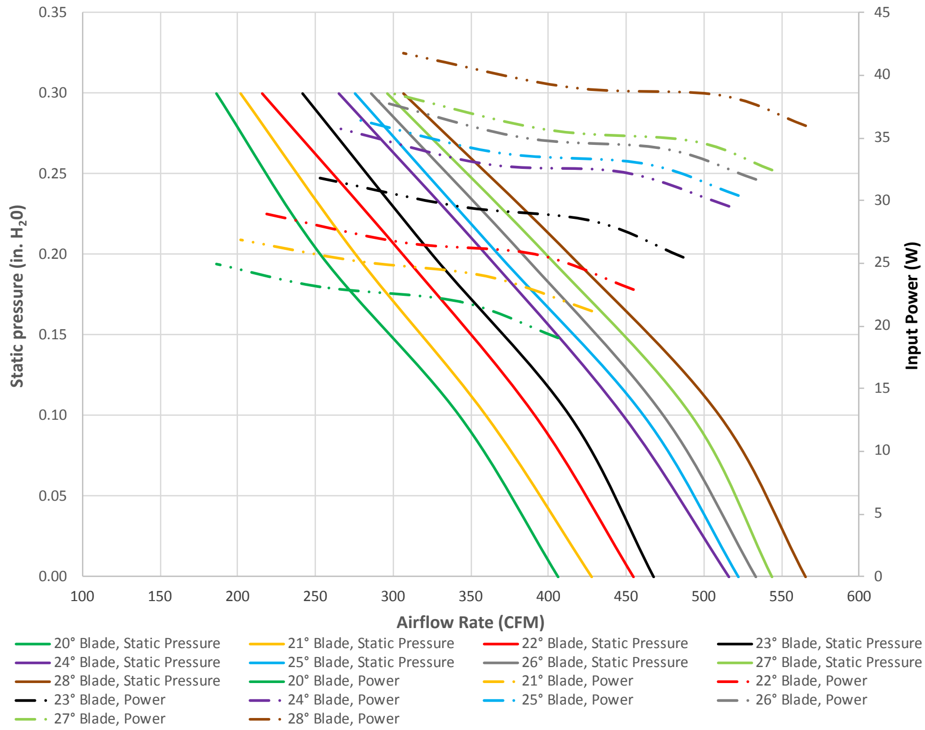

Fig. 20. Static pressure and input power versus airflow rate for a 38–50 W PMS evaporator fan motor with 10-in. fan blades pitched from 20° to 28°.

Fig. 21 shows static pressure and input power versus airflow rate for a 38–50 W PMS evaporator fan motor with 17° to 24° pitched 12-in. fan blades. At a static pressure of 0.3 in. H_2O, the airflow rate was 428 CFM and the input power was 39.9 W for a 17° pitched fan blade, while the airflow rate was 685 CFM and the input power was 85.0 W for a 24° pitched fan blade. At a static pressure of 0.0 in. H_2O, the airflow rate was 654 CFM and the input power was 23.6 W for a 17° pitched fan blade, while the airflow rate was 913 CFM and the input power was 56.3 W for a 24° pitched fan blade.

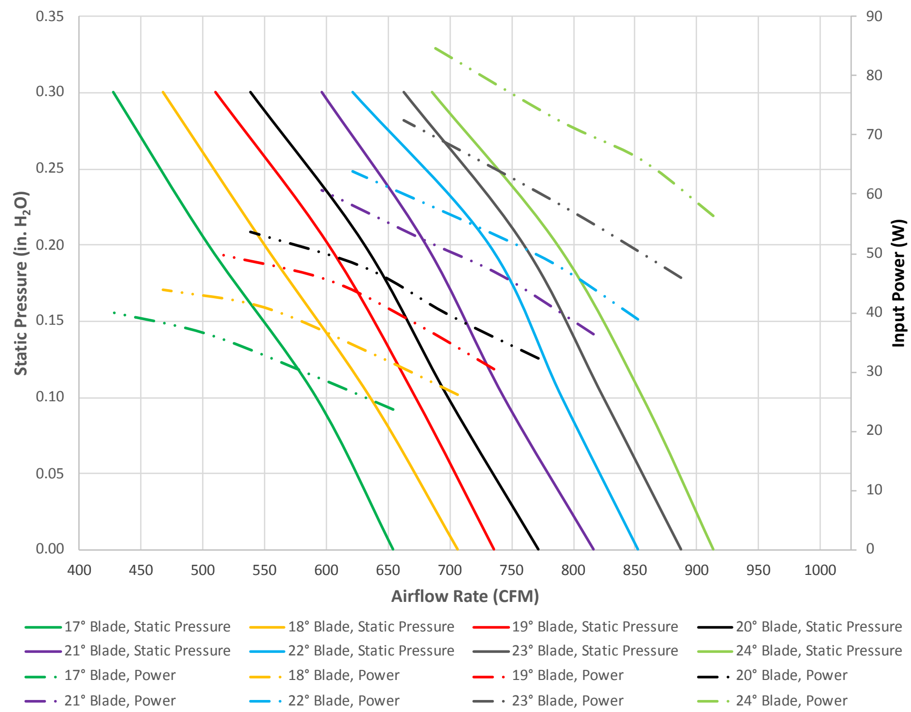

Fig. 21. Static pressure and input power versus airflow rate for a 38–50 W PMS evaporator fan motor with 12-in. fan blades pitched from 17° to 24°.

3.2.2.3 Fan Blade Selection Procedure

The airflow test set-up described in Section 3.2.1 was used to select appropriate fan blades for the retrofit PMS motors. In an effort to match the airflow rate between the incumbent motor/fan assembly, operating at a nominal 1550 RPM, and the retrofit PMS motor/fan assembly, operating at a synchronous 1800 RPM, an appropriately pitched fan blade must be installed in the PMS motor/fan assembly. To that end, a family of fan curves (static pressure vs airflow rate and electrical power input vs airflow rate) was generated for the 6–12 W PMS motor/fan assemblies with 8-inch fan blades pitched from 17 to 32 degrees. A similar set of curves was generated for the 38–50 W PMS motors paired with 10 and 12-inch blades. Various incumbent motor/fan assemblies, removed from the field test sites discussed in Section 4, were also tested in the laboratory airflow test chamber and their fan curves were generated.

To determine the incumbent display case system impedance (static pressure) and the incumbent motor/fan assembly operating point, measurements of the electrical power supplied to the incumbent motor/fan assembly were taken in the field. The operating point and airflow rate of the incumbent motor/fan assembly in the incumbent display case were then determined by locating the measured electrical power on the plot of electrical power input versus airflow rate from the airflow test done in the laboratory. An appropriately pitched fan blade was then installed in the PMS motor/fan assembly to replicate the airflow rate and static pressure of the incumbent motor/fan assembly in the vicinity of its operating point. This operating point represents the impedance of the incumbent display case.

3.2.2.4 Selection of Fan Blade Pitch for 6–12 W PMS Evaporator Fan Motors

Fig. 22 illustrates the procedure discussed above to select an appropriate fan blade for the 6–12 W PMS motor/fan assembly to match the airflow rate of the incumbent motor/fan assembly. Fig. 22 shows the static pressure and input power versus airflow rate for a 12 W EC evaporator motor/fan assembly and a 6–12 W PMS evaporator motor/fan assembly with a 22° pitched 8-in. fan blade. For the EC evaporator fan motor at a static pressure of 0.2 in. H_2O, the airflow rate was 138 CFM and the input power was 21.3 W, while at 0.0 in H_2O, the airflow rate was 229 CFM and the input power was 20.4 W. For the PMS evaporator fan motor with a 22° pitched fan blade at a static pressure of 0.2 in. H_2O, the airflow rate was 137 CFM and the input power was 11.9 W, while at 0.0 in H_2O, the airflow rate was 278 CFM and the input power was 8.3 W. Thus, for the same airflow rate at 0.2 in. H_2O, the PMS motor/fan assembly required 44% less input power than the EC motor/fan assembly. At 0.0 in. H_2O, the PMS motor/fan assembly required 59% less input power than the EC motor/fan assembly, while providing 21% more airflow rate.

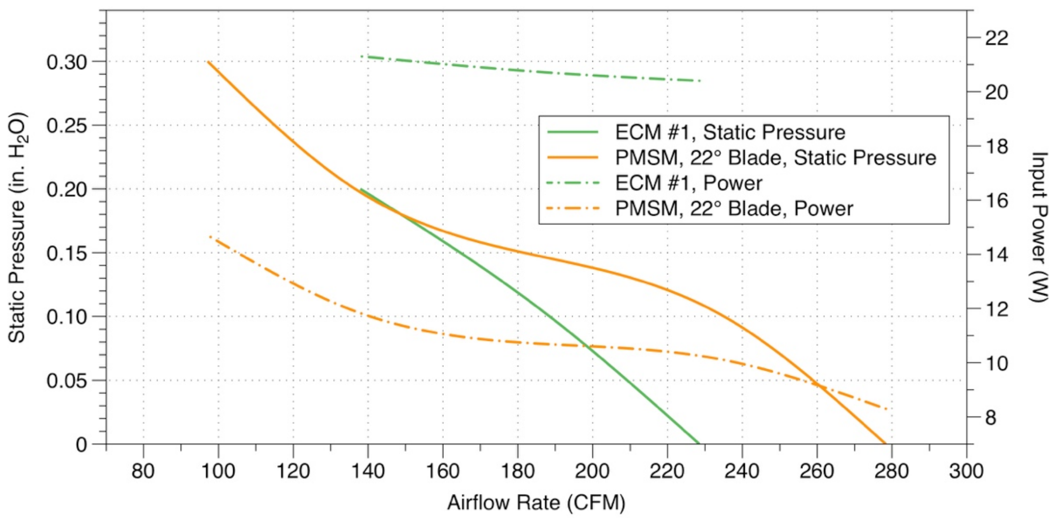

Fig. 22. Static pressure and input power versus airflow rate for a 9-watt EC evaporator fan motor and a 6–12 W PMS evaporator fan motor with a 22° pitched 8-in. fan blade.

3.2.2.5 Selection of Fan Blade Pitch for 38–50 W PMS Evaporator Fan Motors

Fig. 23 illustrates the procedure discussed above to select an appropriate fan blade for the 38–50 W PMS motor/fan assembly to match the airflow rate of the incumbent motor/fan assembly. Fig. 23 shows the static pressure and input power versus airflow rate for a 38 W PSC evaporator motor/fan assembly and a 38–50 W PMS evaporator motor/fan assembly with a 20° pitched 10-in. fan blade. For the PSC evaporator fan motor at a static pressure of 0.3 in. H_2O, the airflow rate was 170 CFM and the input power was 49.7 W, while at 0.0 in H_2O, the airflow rate was 435 CFM and the input power was 43.1 W. For the PMS evaporator fan motor with a 20° pitched fan blade at a static pressure of 0.3 in. H_2O, the airflow rate was 187 CFM and the input power was 25.0 W, while at 0.0 in H_2O, the airflow rate was 406 CFM and the input power was 19.1 W. Thus, the PMS motor/fan assembly required approximately 55% less input power for the same airflow rate.

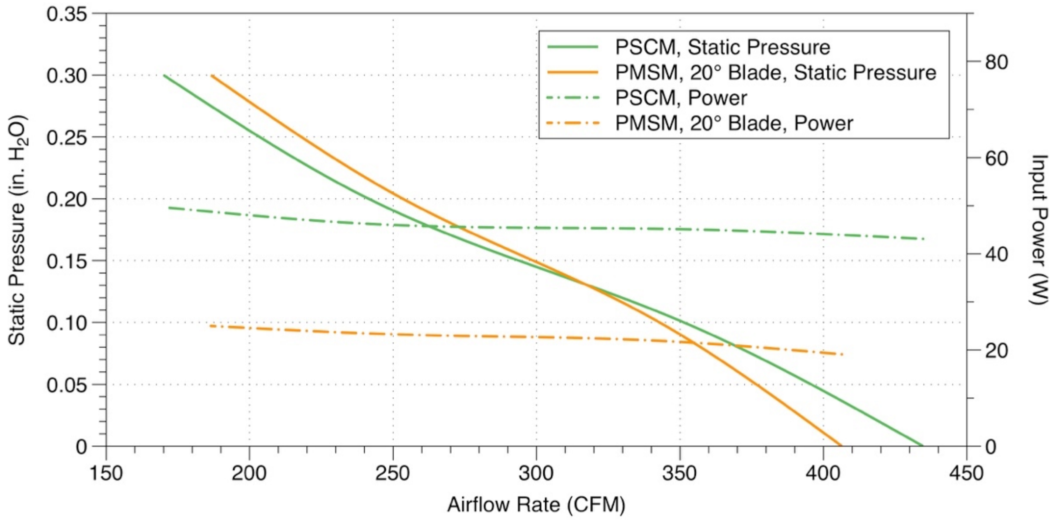

Fig. 23. Static pressure and input power versus airflow rate for a 38-watt PSC evaporator fan motor and a 38–50 W PMS evaporator fan motor with a 20° pitched 10-in. fan blade.

3.2.2.6 PMS and Incumbent Motor/Fan Assembly Airflow Performance Comparison

As discussed in Section 4.3, the culmination of the field evaluation of fan motor technologies was a whole-store retrofit conducted at a supermarket located in Dublin, OH, within the Columbus metropolitan area. Pre- and post-retrofit measurement of evaporator fan motor power in medium- and low-temperature refrigerated display cases and walk-in coolers/freezers was performed. Several incumbent motors that were replaced in the whole-store retrofit were returned to the laboratory for airflow testing.

It is not practical or cost effective to perform laboratory airflow testing on every motor/fan assembly replaced in a whole-store retrofit. Therefore, prior to the whole-store retrofit, a wide variety of incumbent motor/fan assemblies were tested in the laboratory to determine their airflow performance. Based on the results of these tests, the PMS motor manufacturer standardized its motor/fan blade pitch configuration as follows:

- 6–12 W PMS motor, 8-inch fan blade pitch: 25°
- 38–50 W PMS motor, 10-inch fan blade pitch: 22°
- 38–50 W PMS motor, 12-inch fan blade pitch: 18°

Thus, during the whole-store retrofit, 6–12 W and 38–50 W PMS motor/fan assemblies with the standardized blade pitches shown above were installed. To validate these standard pitched blades, several incumbent motors that were replaced in the whole-store retrofit were returned to the laboratory for comparison airflow testing.

Fig. 24 compares the airflow performance of a 6–12 W PMS evaporator fan motor with a 25° pitched 8-in. fan blade to various 6–12 W EC evaporator fan motors with 8-in. fan blades. It can be seen that the static pressure versus airflow rate of the PMS motor compares favorably to that of the EC motors, and delivers approximately the same airflow rate. Thus, the 25° pitched 8-in. fan blade appears to be the correct choice to match the airflow performance of the EC motors. It can also be seen that the input power required by the PMS fan motor was considerably less than that required by the EC motors over the full range of airflow rates.

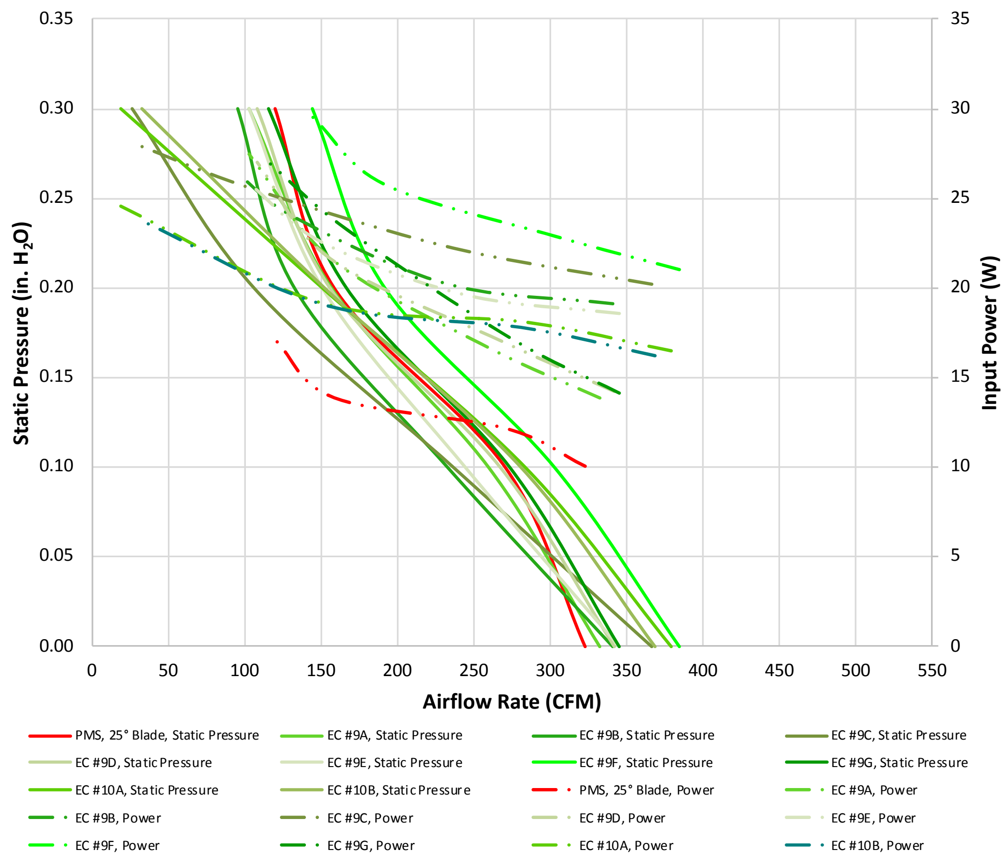

Fig. 24. Static pressure and input power versus airflow rate for various 6–12 W EC evaporator fan motors with 8-in. fan blades and a 6–12 W PMS evaporator fan motor with a 25° pitched 8-in. fan blade.

Fig. 25 compares the airflow performance of a 6–12 W PMS evaporator fan motor with a 25° pitched 8-in. fan blade to various 6–12 W SP evaporator fan motors with 8-in. fan blades. It can be seen that the PMS fan motor with a 25° pitched 8-in. fan blade delivers a higher airflow rate than the vast majority of the SP motors. As seen from Fig. 25, a PMS evaporator fan motor with a 17° pitched 8-in. fan blade would have more closely matched the airflow performance of the SP motors. Therefore, in this case, a 17° pitched blade would be a better choice than the standard 25° pitched blade. Fig. 25 shows that the input power required by the PMS fan motor with a 25° pitched blade was considerably less than that required by the SP motors over the full range of airflow rates. Fig. 25 also shows that additional energy savings could have been achieved with the 17° pitched blade had it been used instead.

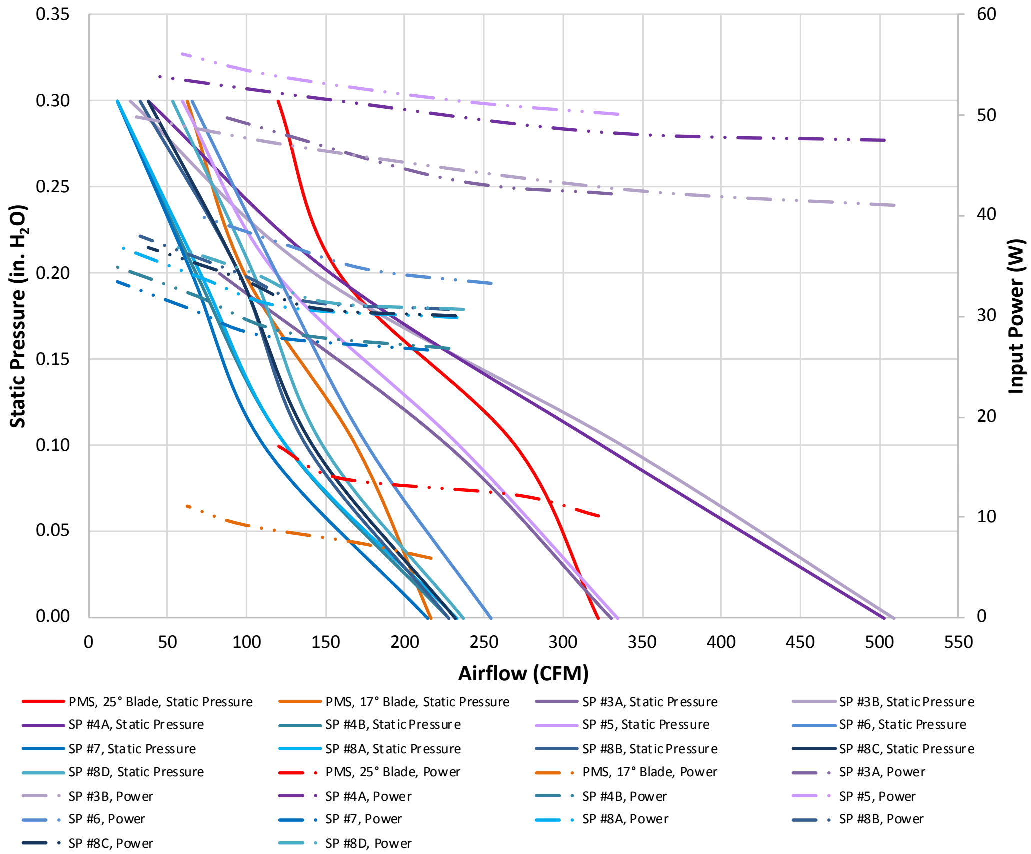

Fig. 25. Static pressure and input power versus airflow rate for various 6–12 W SP evaporator fan motors with 8-in. fan blades, a 6–12 W PMS evaporator fan motor with a 25° pitched 8-in. fan blade, and a 6–12 W PMS evaporator fan motor with a 17° pitched 8-in. fan blade.

Fig. 26 compares the airflow performance of a 38–50 W PMS evaporator fan motor with a 22° pitched 10-in. fan blade to various 38–50 W PSC evaporator fan motors with 10-in. fan blades. It can be seen that the PMS fan motor with a 22° pitched 10-in. fan blade delivers a higher airflow rate than the PSC motors. As seen from Fig. 26, a PMS evaporator fan motor with a 20° pitched 10-in. fan blade more closely matches the airflow performance of the PSC motors. Therefore, in this case, a 20° pitched blade would have been a better choice than the standard 22° pitched blade. Fig. 26 shows that the input power required by the PMS fan motor with a 22° pitched blade was considerably less than that required by the PSC motors over the full range of airflow rates. Fig. 26 also shows that additional energy savings could have been achieved with the 20° pitched blade.

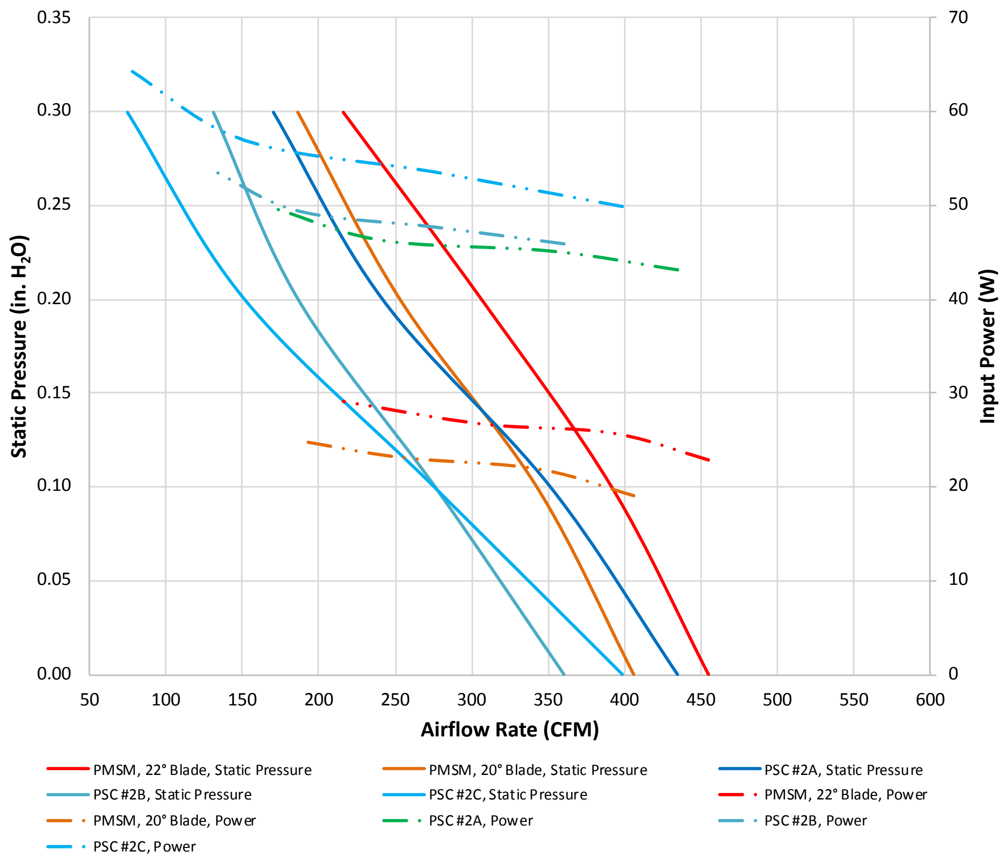

Fig. 26. Static pressure and input power versus airflow rate for various 38–50 W PSC evaporator fan motors with 10-in. fan blades, a 38–50 W PMS evaporator fan motor with a 22° pitched 10-in. fan blade, and a 38–50 W PMS evaporator fan motor with a 20° pitched 10-in. fan blade.

Fig. 27 compares the airflow performance of a 38–50 W PMS evaporator fan motor with an 18° pitched 12-in. fan blade to various 38–50 W PSC evaporator fan motors with 12-in. fan blades. It can be seen that the static pressure versus airflow rate of the PMS motor compares favorably to that of the PSC motors and delivers approximately the same airflow rate. Thus, the 18° pitched 12-in. fan blade appears to be the correct choice to match the airflow performance of the PSC motors. It can also be seen that the input power required by the PMS fan motor was considerably less than that required by the PSC motors over the full range of airflow rates.

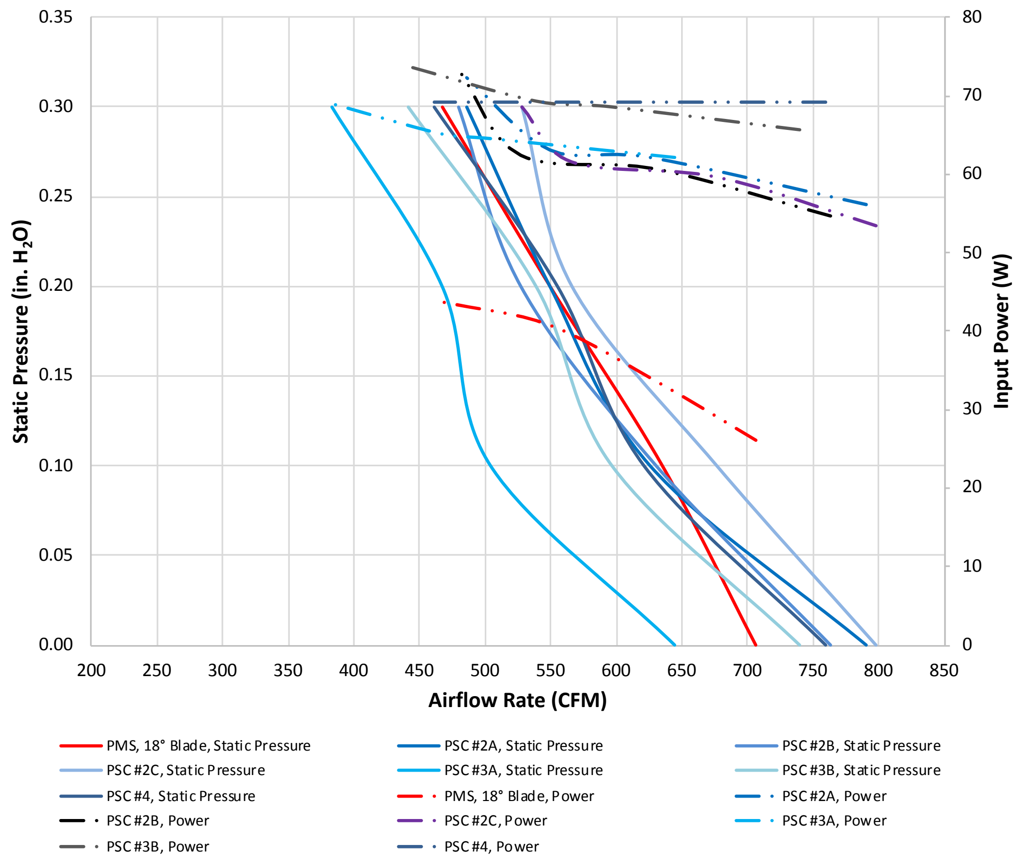

Fig. 27. Static pressure and input power versus airflow rate for various 38–50 W PSC evaporator fan motors with 12-in. fan blades and a 38–50 W PMS evaporator fan motor with an 18° pitched 12-in. fan blade.

Fig. 28 compares the airflow performance of a 38–50 W PMS evaporator fan motor with an 18° pitched 12-in. fan blade to a 38–50 W EC evaporator fan motor with a 12-in. fan blade and a 38–50 W SP evaporator fan motor with a 12-in. fan blade. It can be seen that the PMS fan motor with an 18° pitched 12-in. fan blade delivers a higher airflow rate than the EC or SP motors. As seen from Fig. 28, a PMS evaporator fan motor with a 17° pitched 12-in. fan blade more closely matches the airflow performance of the EC or SP motors, although it still delivers considerably more airflow than either the EC or SP motors. Therefore, in this case, a 17° pitched blade would be a better choice than the standard 18° pitched blade. Fig. 28 shows that the input power required by the PMS fan motor with a 18° pitched blade was considerably less than that required by the SP motor and somewhat less than that required by the EC motor over the full range of airflow rates. Fig. 28 also shows that additional energy savings could be achieved with the 17° pitched blade.

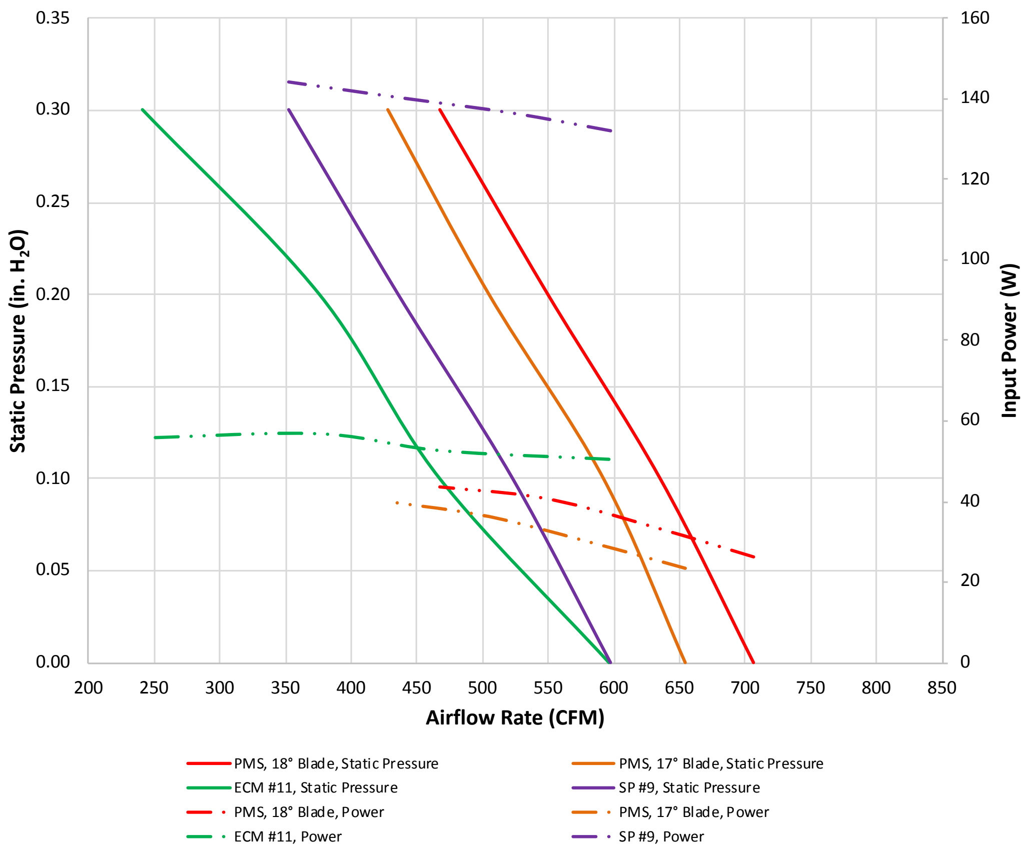

Fig. 28. Static pressure and input power versus airflow rate for a 38–50 W EC evaporator fan motor with a 12-in. fan blade, a 38–50 W SP evaporator fan motor with a 12-in. fan blade, a 38–50 W PMS evaporator fan motor with an 18° pitched 12-in. fan blade, and a 38–50 W PMS evaporator fan motor with a 17° pitched 12-in. fan blade.

In summary, the standardized PMS motor/fan assemblies used for the whole-store retrofit produced airflow rates that were greater than or equivalent to the incumbent motor/fan assemblies. Therefore, the energy savings realized by the PMS motor/fan assembly retrofit was due to the higher efficiency of the PMS motor and did not result in a reduced airflow rate or reduced refrigeration effect.

4. FIELD EVALUATION OF FAN MOTOR TECHNOLOGIES

The U.S. DOE has recently supported field demonstrations to quantify the energy savings realized by switching from shaded-pole, PSC, or EC evaporator fan motors to PMS motors (Becker and Fricke 2016). The demonstration consisted of side-by-side and pre- and post-retrofit measurement of the power consumption of PMS and shaded-pole, PSC, or EC evaporator fan motors in refrigerated display cases and walk-in coolers/freezers.

4.1 DISPLAY CASE EVAPORATOR FAN MOTORS

Field evaluation of refrigerated display case evaporator fan motors was accomplished by performing side-by-side comparisons of 6–12 W PMS motors to 6–12 W shaded-pole and EC evaporator fan motors.

4.1.1 Field Test Sites

At each test site, either one display case was used, in which an equal number of incumbent and PMS evaporator fan motors were installed (with one motor type in each half of the display case) or two identical display cases were used, in which one display case contained the incumbent fan motors while the other case contained an equal number of PMS fan motors. During the retrofit of PMS fan motors at each test site, care was taken to match the airflow rate between the incumbent fans and the PMS fans to within 5% by using appropriately pitched fan blades on the PMS motors. Details of the procedure to match airflow rate between incumbent and PMS motor/fan assemblies is provided in Section 3.2.2.3.

A total of six test sites were used for the side-by-side field evaluation of the various 6–12 W evaporator fan motor technologies. The location of each test site as well as display case descriptions and motor types evaluated are summarized in Table 8. The motors evaluated included shaded pole motors from one manufacturer, EC motors from three manufacturers (denoted as types “A”, “B” and “C”) and PMS motors from one manufacturer.

Table 8. Summary of field test sites for side-by-side comparison of evaporator fan motors in medium-temperature refrigerated display cases

Number and type of fan motor		Display case type	Data collection duration	Location
Electrical circuit A	Electrical circuit B			
Two shaded-pole	Two PMS	One 4.9 m long medium-temperature open multi-deck case	14 months	Kansas City, MO Site #1
Four EC, type A	Four PMS	Two 3.7 m long medium-temperature open multi-deck cases	Five months	Kansas City, MO Site #2
Two EC, type B	Two PMS	Two 2.4 m long medium-temperature open multi-deck cases	17 months	Lee’s Summit, MO
One EC, type B	One PMS	One 2.4 m long medium-temperature open multi-deck case	Six months	San Diego, CA
Three EC, type C	Three PMS	Two 3.7 m long medium-temperature open multi-deck cases, retrofit with doors	Five months	San Antonio, TX Site #1
Two EC, type C	Two PMS	One 3.7 m long medium-temperature open multi-deck case, retrofit with doors	Five months	San Antonio, TX Site #2

Measured quantities at each test site included fan motor power, voltage, current, and power factor, as well as display case discharge and return air temperatures and ambient store temperature. Quantities were measured every 30 seconds and then averaged and recorded every two minutes. Table 9 lists the specifications of the instrumentation used in this study.

Table 9. Instrumentation specifications for side-by-side evaluation of evaporator fan motors

Instrument	Measured quantity	Instrument range	Accuracy
Power Meter	Fan power, current, voltage and power factor	Power: 0 to 600 W Current: 0 to 5 A Voltage: 90 to 600 V	Power: 0.2% Current: 0.4% Voltage: 0.4%
Resistance Temperature Detector (RTD)	Display case discharge and return air temperature	-50 to 260°C	±0.20°C

4.1.2 Field Evaluation Results and Discussion

Fig. 29 shows an example of the fan motor energy performance data obtained from one of the Kansas City test sites, where the performance of two shaded pole and two PMS evaporator fan motors in one 4.9 m long medium-temperature open multi-deck display case were compared side-by-side. Average evaporator fan power, current and power factor are shown in Fig. 29. It can be seen that the two PMS motors consumed 79% less power while drawing 82% less current than the two shaded pole motors. In addition, the power factor for the PMS motors was 20% higher than that of the shaded pole motors. Data from the other test sites show similar trends.

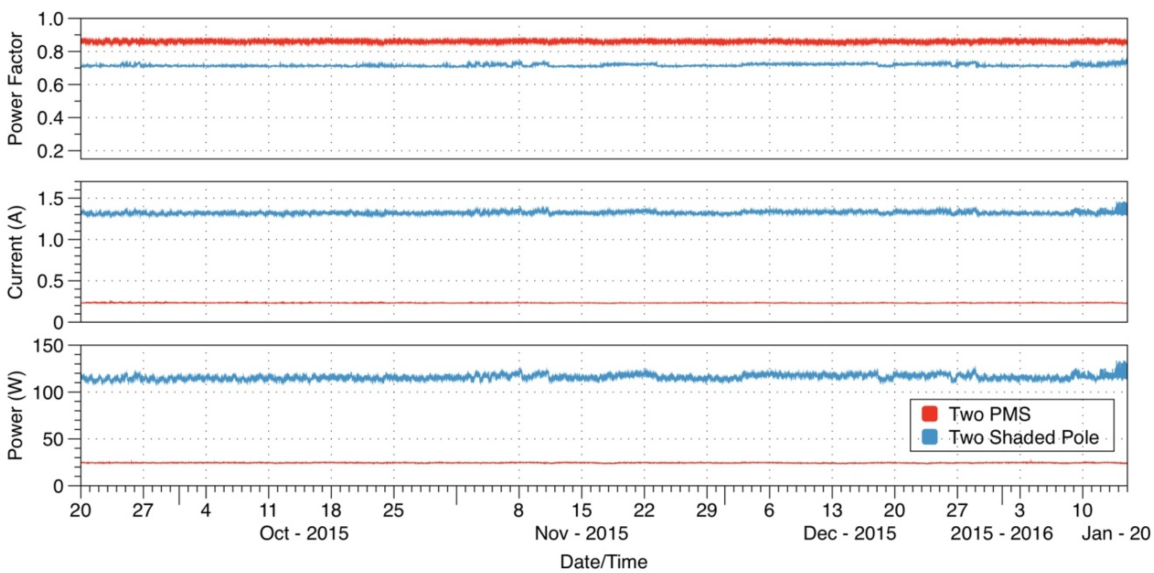

Fig. 29. Shaded-pole and PMS evaporator fan motor performance, including fan power, current and power factor, Kansas City, MO Test Site #1.

A summary of evaporator fan motor performance data for all the test sites is given in Table 10. From Table 10, it can be seen that, on average, the PMS motors consumed 79% less power and drew 82% less current than the shaded pole motors. lso, the PMS motors consumed on average 34% less power and 49% less current than the EC motors. In addition, the PMS motors exhibited an average power factor of approximately 0.82, which was on average 40% greater than that of the existing evaporator fan motors.

Power factors for San Antonio, TX Site #1 are not reported because the evaporator fan motors were on the same circuit as the door heaters, which skewed the data.

Table 10. Summary of refrigerated display case evaporator fan motor energy performance

Fan motor type	Average power, per motor (W)	Average current, per motor (A)	Average power factor	Site location
Shaded-Pole	58.1	0.662	0.718	Kansas City, MO Site #1
PMS	12.2	0.117	0.860	
Difference (%)	-79.0	-82.3	+19.8	
EC, type A	9.7	0.136	0.606	Kansas City, MO Site #2
PMS	7.4	0.088	0.718	
Difference (%)	-23.3	-35.3	+18.5	
EC, type B	24.1	0.321	0.621	Lee's Summit, MO
PMS	13.2	0.126	0.868	
Difference (%)	-45.2	-60.7	+39.8	
EC, type B	20.9	0.380	0.459	San Diego, CA
PMS	12.5	0.119	0.865	
Difference (%)	-40.2	-68.7	+88.5	
EC, type C	23.6	0.256	--	San Antonio, TX Site #1
PMS	13.9	0.148	--	
Difference (%)	-41.1	-42.2	--	
EC, type C	16.4	0.228	0.620	San Antonio, TX Site #2
PMS	13.0	0.138	0.811	
Difference (%)	-20.7	-39.5	+30.8	

Table 11 summarizes the average discharge and return air temperatures and their difference, ΔT, for the refrigerated display cases. The effect of evaporator fan motor type was negligible on the discharge and return air temperatures, which did not vary by more than approximately 2°C between PMS and shaded-pole or EC motors. This is an indication that the airflow rate and refrigerating effect within the display cases was not affected by replacing the incumbent fans and motors with the PMS fans and motors. The discharge air temperature sensor at the San Antonio, TX Site #1 failed to report data.

Table 11. Summary of refrigerated display case discharge and return air temperatures

Fan motor type	Average discharge air temperature (°C)	Average return air temperature (°C)	Average ΔT (°C)	Site location
Shaded-Pole	0.94	4.82	3.88	Kansas City, MO Site #1
PMS	1.12	5.05	3.93	
Absolute Difference (°C)	0.18	0.23	0.05	
EC, type A	2.16	6.90	4.74	Kansas City, MO Site #2
PMS	2.18	6.31	4.12	
Absolute Difference (°C)	0.02	0.59	0.62	
EC, type B	2.48	8.69	6.21	Lee's Summit, MO
PMS	1.72	6.51	4.78	
Absolute Difference (°C)	0.76	2.18	1.42	
EC, type B	1.91	6.34	4.43	San Diego, CA
PMS	2.22	7.95	5.73	
Absolute Difference (°C)	0.31	1.61	1.30	

Fan motor type	Average discharge air temperature (°C)	Average return air temperature (°C)	Average ΔT (°C)	Site location
EC, type C	--	1.07	--	San Antonio, TX Site #1
PMS	0.13	1.15	1.02	
Absolute Difference (°C)	--	0.08	--	
EC, type C	-0.77	0.11	0.89	San Antonio, TX Site #2
PMS	-0.59	1.68	2.27	
Absolute Difference (°C)	0.18	1.57	1.39	

4.2 WALK-IN COOLER/FREEZER EVAPORATOR FAN MOTORS

4.2.1 Field Test Sites

Two field test sites were selected to evaluate the performance of the larger 38 to 50 W PMS evaporator fan motors in walk-in cooler/freezer applications. One supermarket was located in South Burlington, VT while the other was located in Colchester, VT. At each supermarket, two walk-in units were selected for investigation: one walk-in dairy cooler and one walk-in freezer. Both supermarkets were part of the same brand chain.

The walk-in dairy cooler selected at the South Burlington, VT store contained four evaporators, with each evaporator having three evaporator fan motors each, for a total of 12 evaporator fan motors. The walk-in freezer selected at the South Burlington, VT store contained three evaporators with each evaporator unit having four evaporator fan motors each, for a total of 12 evaporator fan motors, however, one of the units was not in service, so only 8 motors were tested in the freezer.

The dairy walk-in cooler selected at the Colchester, VT store contained three evaporators, with each evaporator having four evaporator fans, for a total of 12 evaporator fan motors. The walk-in freezer selected at the Colchester, VT store contained two evaporators with each evaporator having five evaporator fan motors, for a total of 10 evaporator fan motors.

A summary of the number of evaporators and evaporator fan motors used in the walk-in cooler/freezer evaporator fan motor evaluation is provided in Table 12.

Table 12. Summary of walk-in coolers/freezer evaporators and evaporator fans

Supermarket location	Walk-in type	Number of evaporators	Number of fans per evaporator	Total number of evaporator fans
South Burlington, VT	Dairy Cooler	4	3	12
	Freezer	2	4	8
Colchester, VT	Dairy Cooler	3	4	12
	Freezer	2	5	10

The incumbent evaporator fan motors in each of the four walk-ins were of unknown type. Fan blade selection for the retrofit PMS motors was based on the original equipment fan motor/blade combination supplied with each evaporator, per the evaporator manufacturer. Actual airflow testing of the incumbent motors was not possible at these VT sites.

Measured quantities at each test site included walk-in evaporator fan motor power, voltage, current, and power factor. In addition, air temperature near a centrally located evaporator in each walk-in cooler or freezer was measured using a small self-contained temperature data logger. Average evaporator fan motor electric power quantities and air temperature were recorded at one-minute intervals during the test period. Table 13 list the specifications of the instrumentation used in this study.

Table 13. Instrumentation specifications for pre- and post-retrofit evaluation of walk-in cooler/freezer evaporator fan motors

Instrument	Measured quantity	Instrument range	Accuracy
Portable Power Meter Data Logger	Fan power, current, voltage and power factor	Power: 0 to 1200 W Power Factor: 0 to 1 Current: 0 to 20 A Voltage: 0 to 600 V	Power: 0.2% Power Factor: 0.2% Current: 0.2% Voltage: 0.2%
Portable Temperature Data Logger	Walk-in cooler or freezer air temperature	-210 to 760°C	±0.6°C

Table 14 summarizes the duration of evaporator fan motor performance data collection, pre- and post-retrofit, for each walk-in at the two supermarkets.

Table 14. Pre- and post-retrofit walk-in evaporator fan motor performance data collection duration

Store location/walk-in	Data collection duration (days)	
	Pre-retrofit	Post-retrofit
South Burlington, VT: Walk-In Dairy Cooler	55	20
South Burlington, VT: Walk-In Freezer	55	45
Colchester, VT: Walk-In Dairy Cooler	45	50
Colchester, VT: Walk-In Freezer	45	50

It was intended to have the evaporator coils in each walk-in cleaned prior to data collection. Shortly after the instrumentation was installed at each store, a refrigeration service provider was contracted to clean the evaporator coils, however, as discussed below, there was evidence that evaporator coil cleaning was not performed uniformly, or at all, for each walk-in investigated.

4.2.2 Field Evaluation Results and Discussion

The results of the pre- and post-retrofit of walk-in evaporator fan motors at the South Burlington, VT and Colchester, VT supermarkets is given below. The South Burlington store discussion includes results from the four dairy walk-in cooler evaporators (far-left, left, right and far-right) and the two freezer evaporators (left and middle; the right unit was not in service). The Colchester store discussion includes results from the three dairy walk-in cooler evaporators (left, middle and right) and the two walk-in freezer evaporators (left and right).

4.2.2.1 Walk-In Cooler – South Burlington, VT Supermarket

As shown in Table 12, the dairy walk-in cooler at the South Burlington, VT, supermarket contained four evaporators, which will be designated as the far-left, left, right and far-right evaporators in the discussion below. Each of these evaporator coils contained three evaporator fan motors.

Fig. 30 shows the evaporator fan motor power, current and power factor for the far-left evaporator in the walk-in dairy cooler at the South Burlington, VT, store for the period 20 April 2017 through 6 July 2017. The incumbent evaporator fan motors were replaced with PMS motors on 16 June 2017.

It can be seen from Fig. 30 that the power and current of the incumbent fan motors decreased on 3 May. As previously noted, it was intended that the evaporator coils would be cleaned prior to the fan motor performance evaluation. It would appear that the coils were cleaned on 3 May 2017, as indicated by the decrease in incumbent evaporator fan power and current noted on 3 May. Assuming this to be the case, the average combined power of the three incumbent fan motors in the far-left evaporator was found to be 360 W during the period 3 May through 16 June.

As shown in Fig. 30, the average combined power of the three PMS fan motors in the far-left evaporator was 144 W during the post-retrofit period 16 June 2017 to 6 July 2017.

Assuming that the total power of the three incumbent evaporator fan motors for the far-left evaporator is on average 360 W, and similarly that the total power of the three PMS evaporator fan motors is on average 144 W, the PMS motors were found to use 60% less power than the incumbent motors.

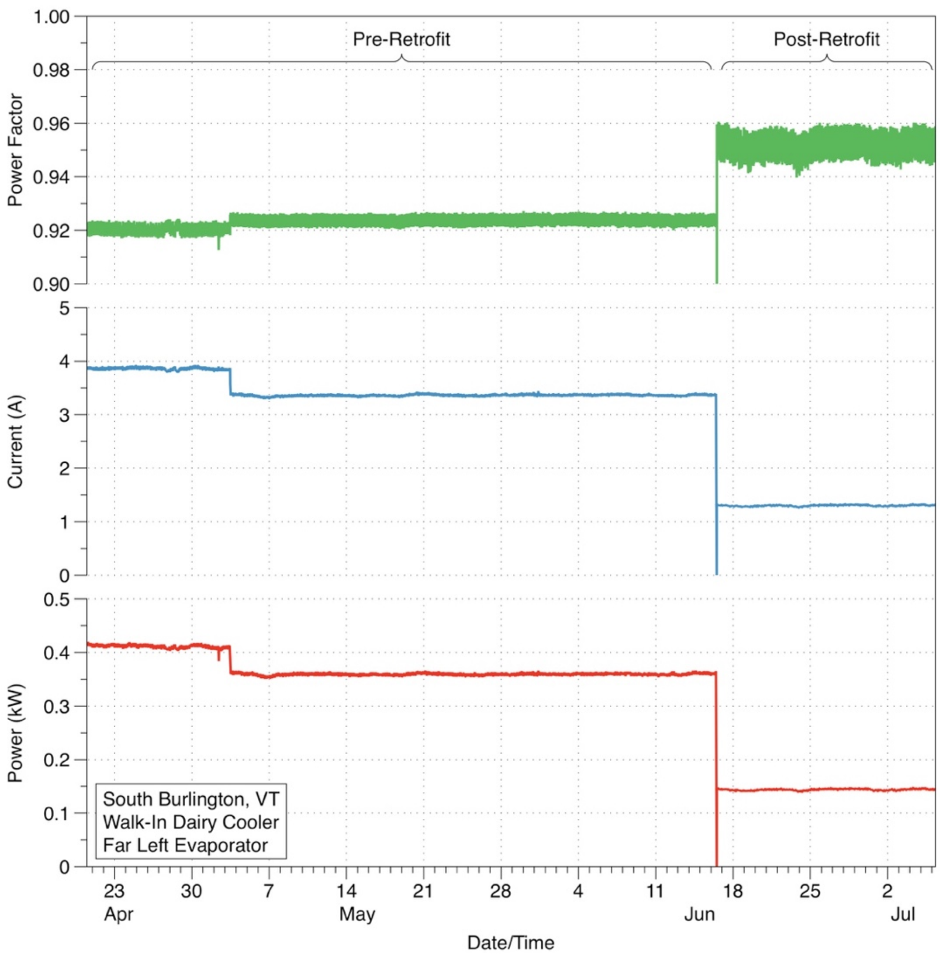

Fig. 30. Pre- and post-retrofit evaporator fan power, current and power factor for the far-left evaporator in the walk-in dairy cooler, South Burlington, VT.

Performance data for the evaporator fan motors in the left, right and far-right evaporator coils in the walk-in dairy cooler at the South Burlington, VT, store exhibited similar behavior as that of the fan motors in the far-left evaporator coil. Detailed performance data for the fan motors in the left, right and far-right evaporators may be found in Appendix A.

A summary of the measured performance of the walk-in dairy cooler evaporator fan motors at the South Burlington, VT, store is given in Table 15, including current, power and power factor. Also shown is the percentage difference between the incumbent and PMS motor performance.

Table 15. Summary of evaporator fan motor performance for the walk-in dairy cooler at the South Burlington, VT, store

Evaporator	Fan motor	Current (A)	Power (W)	Power factor
Far Left	Incumbent	3.36	360	0.924
	PMS	1.30	144	0.952
	Difference (%)	61	60	-3.0
Left	Incumbent	3.49	376	0.928
	PMS	1.38	153	0.950
	Difference (%)	60	59	-2.4
Right	Incumbent	3.18	342	0.918
	PMS	1.23	136	0.937
	Difference (%)	61	60	-2.1
Far Right	Incumbent	3.11	333	0.925
	PMS	1.15	123	0.925
	Difference (%)	63	63	0.0

On average, the walk-in cooler evaporator fan power decreased by 61% following the retrofit of the incumbent fan motors with PMS fan motors. In addition, the current draw was reduced by 61% and the power factor was increased by 1.9% after retrofitting the walk-in cooler evaporator fan motors. Furthermore, the measured evaporator fan motor power, current and power factor data were consistent across the four evaporators during both the pre- and post-retrofit periods, thus providing confidence that the power reduction exhibited post-retrofit is valid and accurate. The incumbent fan motor type is uncertain since the motors were removed and disposed of without noting the motor type; however, it is believed that the incumbent motors were PSC motors since their measured power factor is typical of PSC motors.

4.2.2.2 Walk-In Freezer – South Burlington, VT, Supermarket

As shown in Table 12, the walk-in freezer at the South Burlington, VT, supermarket contained three evaporators, designated as the left, middle and right evaporators in the discussion below. Each of these evaporator coils contained four evaporator fan motors. As noted above, the evaporator fans in the right evaporator were not active during this study, so there will be no further discussion regarding the right evaporator.

Fig. 31 shows the evaporator fan motor power for the left evaporator in the walk-in freezer at the South Burlington, VT, store for the period 20 April 2017 through 3 August 2017. The incumbent evaporator fan motors were replaced with PMS motors on 16 June 2017. It can be seen that evaporator fan motor power was relatively constant prior to the motor retrofit. A significant drop in fan power was noted following the installation of the PMS evaporator fan motors, and power remained constant at this lower level.

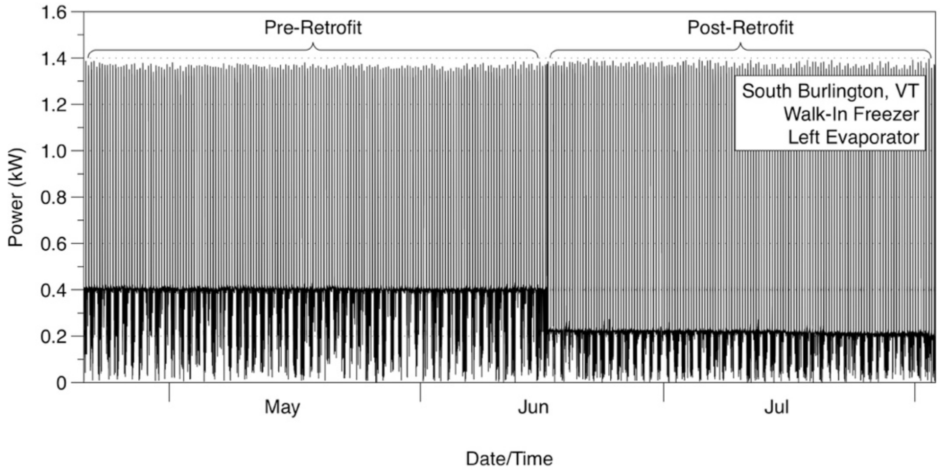

Fig. 31. Pre- and post-retrofit evaporator fan power for the left evaporator in the walk-in freezer, South Burlington, VT.

Fig. 32 shows the total power, current and power factor for the four incumbent fan motors in the left walk-in freezer evaporator for a typical day during the pre-retrofit measurement period. Power fluctuates from zero when the freezer door is open and the fan motor cut-off switch is activated, to an average value of 403 W when the freezer door is closed and the four evaporator fans are operating. The peak power of approximately 1.35 kW occurs three times per day during the defrost cycles, each of which lasts approximately 35 minutes. The peak power occurs because the defrost heaters are on the same electrical circuit as the evaporator fan motors.

Similarly, Fig. 33 shows the total power, current and power factor for the four PMS fan motors in the left walk-in freezer evaporator for a typical day during the post-retrofit measurement period. Power fluctuates from zero when the freezer door is open and the fan motor cut-off switch is activated, to an average value of 216 W when the freezer door is closed and the four evaporator fans are operating. The peak power of approximately 1.35 kW occurs three times per day during the defrost cycles, each of which lasts approximately 35 minutes. The peak power occurs because the defrost heaters are on the same electrical circuit as the evaporator fan motors.

Assuming that the total power of the four incumbent evaporator fan motors for the left evaporator was on average 403 W, and similarly that the total power of the four PMS evaporator fan motors was on average 216 W, the PMS motors were found to use 46% less power than the incumbent motors.

As noted previously, it was intended that the evaporator coils would be cleaned prior to the fan motor performance evaluation. Since no significant decrease in fan motor power was noted during the pre-retrofit data collection, it would appear that the left freezer coil at the South Burlington, VT, store was not cleaned.

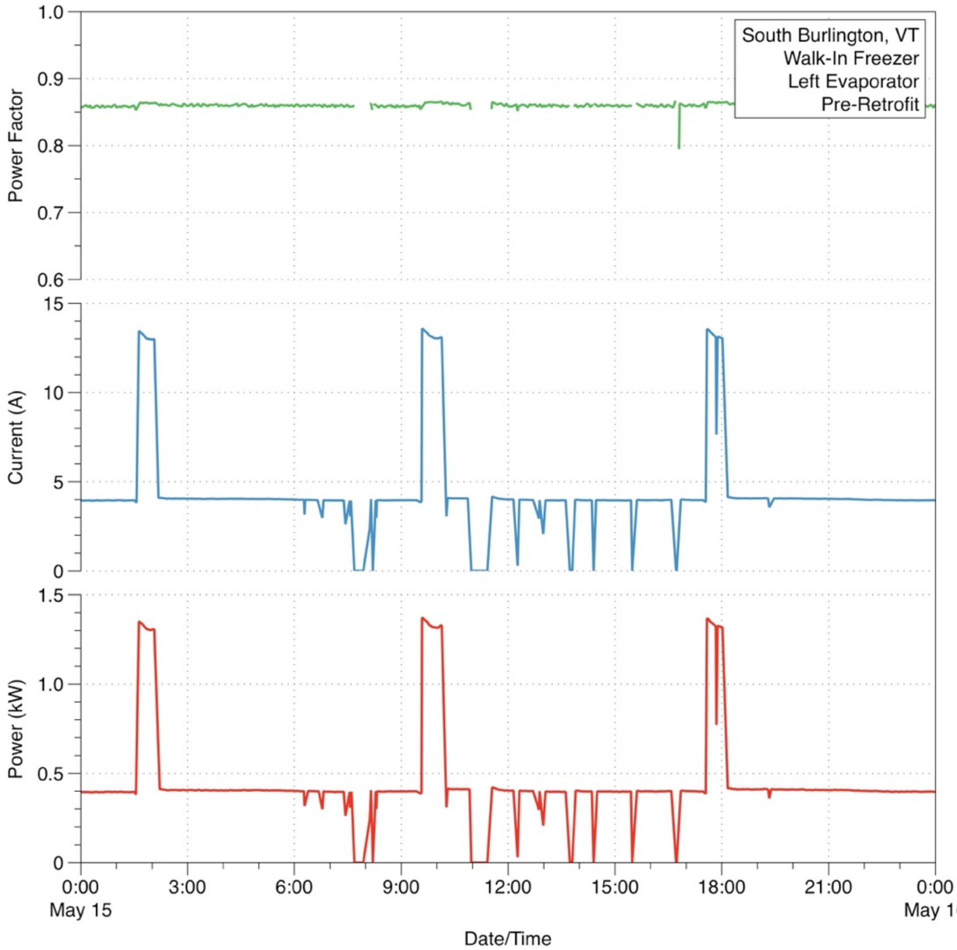

Fig. 32. Pre-retrofit evaporator fan power, current and power factor for the left evaporator in the walk-in freezer, South Burlington, VT, for 15 May 2017 (typical).

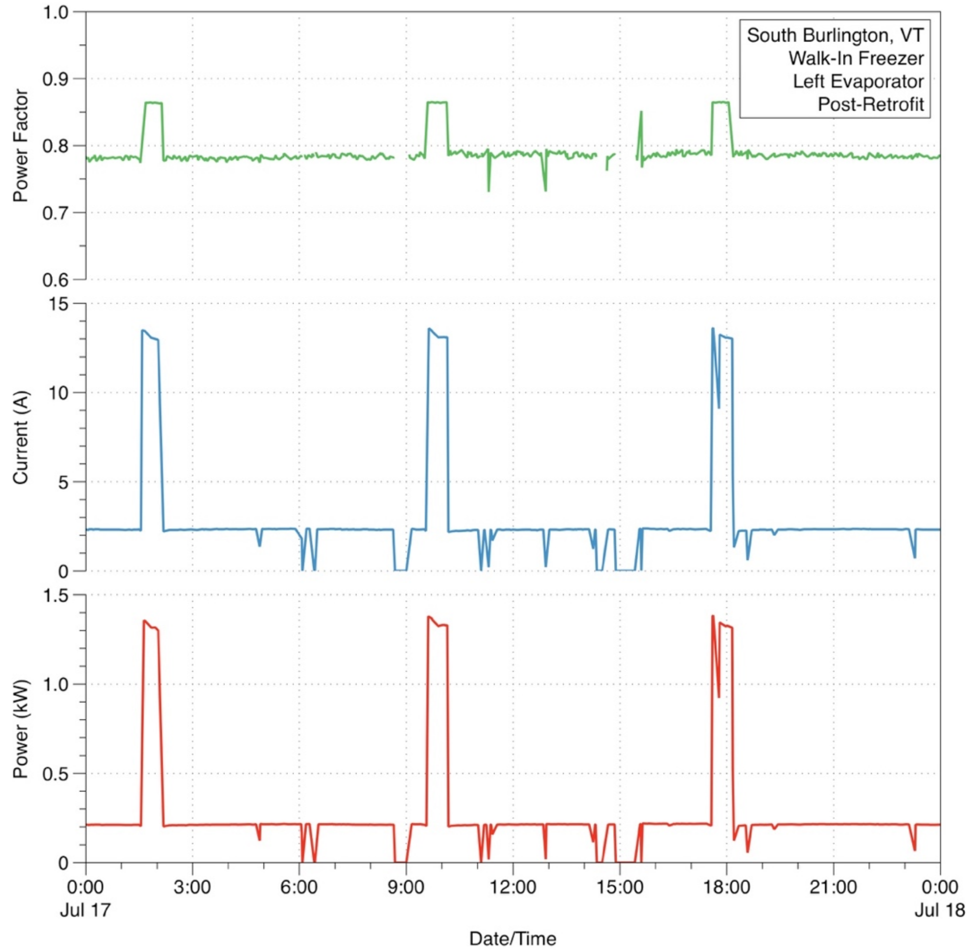

Fig. 33. Post-retrofit evaporator fan power, current and power factor for the left evaporator in the walk-in freezer, South Burlington, VT, for 17 July 2017 (typical).

Performance data for the evaporator fan motors in the middle evaporator coil in the walk-in freezer at the South Burlington, VT, store exhibited similar behavior as that of the fan motors in the left evaporator. Detailed performance data for the fan motors in the middle evaporator may be found in Appendix A.

A summary of the measured performance of the walk-in freezer evaporator fan motors at the South Burlington, VT, store is given in Table 16, including current, power and power factor. Also shown is the percentage difference in performance between the incumbent and PMS motors.

Table 16. Summary of evaporator fan motor performance for the walk-in freezer at the South Burlington, VT, store

Evaporator	Motor	Current (A)	Power (W)	Power factor
Left	Incumbent	4.01	403	0.860
	PMS	2.34	216	0.787
	Difference (%)	42	46	8.5
Middle	Incumbent	4.26	416	0.842
	PMS	2.37	207	0.753
	Difference (%)	44	50	11

On average, the walk-in freezer evaporator fan power decreased by 48% following the retrofit of the incumbent fan motors with PMS fan motors. In addition, the current draw was reduced by 43% and the power factor was reduced by 9.8% after retrofitting the walk-in freezer evaporator fan motors. Furthermore, the measured evaporator fan motor power, current and power factor data are consistent across the two evaporators during both the pre- and post-retrofit periods, thus providing confidence that the power reduction exhibited post-retrofit is valid and accurate. Furthermore, the results at the South Burlington, VT, test site are consistent with the data gathered at the full store retrofit in Dublin, OH, discussed in Section 4.3, which provides further confidence in the data.

4.2.2.3 Walk-In Cooler - Colchester, VT Supermarket

As shown in Table 12, the dairy walk-in cooler at the Colchester, VT, supermarket, contained three evaporators, which will be designated as the left, middle and right evaporators in the discussion below. Each of these evaporator coils contained four evaporator fan motors.

Fig. 34 shows the evaporator fan motor power for the left evaporator in the walk-in dairy cooler in Colchester, VT, for the period 20 April 2017 through 28 August 2017. The incumbent evaporator fan motors were replaced with PMS motors on 7 June 2017.

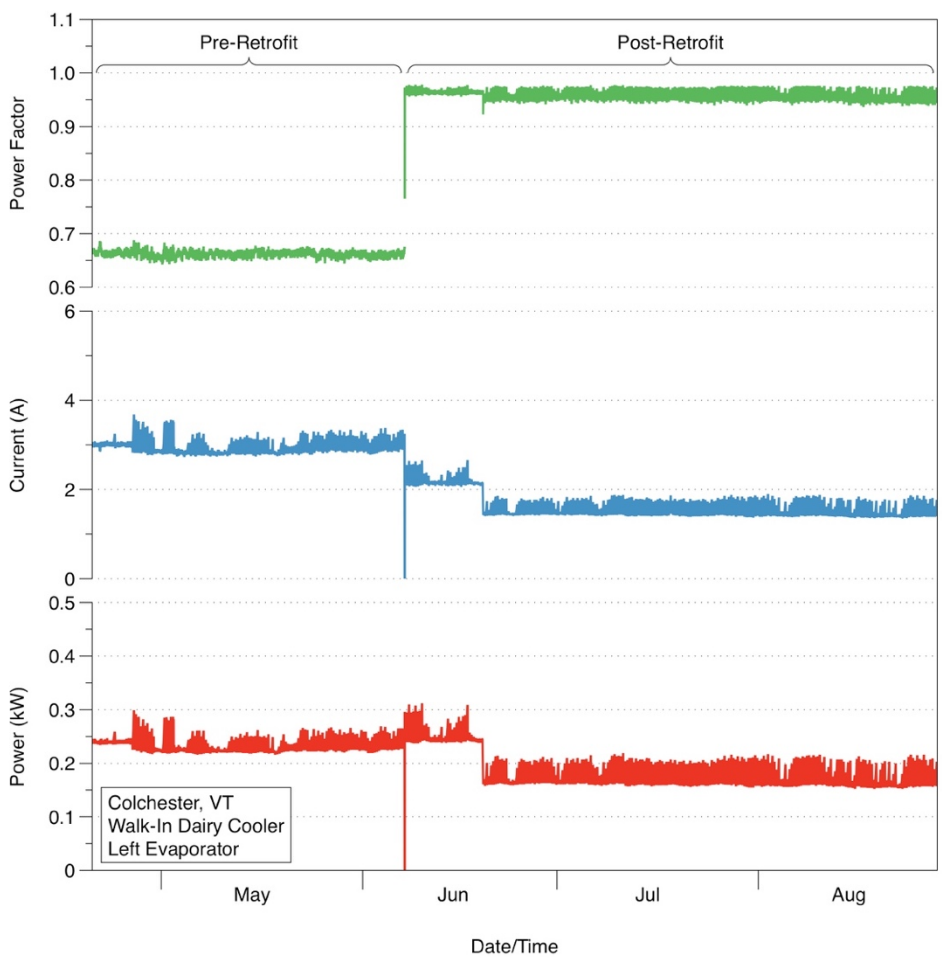

Fig. 34. Pre- and post-retrofit evaporator fan power, current and power factor for the left evaporator in the walk-in dairy cooler, Colchester, VT.

It can be seen from Fig. 34 that the power of the incumbent fan motors decreased slightly around 30 April 2017. As previously noted, it was intended that the evaporator coils would be cleaned prior to the fan motor performance evaluation. It would appear that the coils were cleaned around 30 April 2017, as indicated by the slight drop in evaporator fan power shown in Fig. 34. The average power of the incumbent fan motors during the period 30 April to 7 June was 234 W, while the initial incumbent fan motor power was approximately 240 W prior to coil cleaning.

As shown in Fig. 34, the initial PMS motor power was approximately 240 W, which then decreased dramatically to an average of 176 W from 19 June 2017 to 28 August 2017. The reason for the sudden decrease in evaporator fan power exhibited post-retrofit on 19 June 2017 is unknown.

Assuming the incumbent evaporator fan motor power is approximately 234 W, and similarly that the PMS evaporator fan motor power is approximately 176 W, the PMS motors were found to use 25% less power than the incumbent motors. However, due to the anomalies in the data, these results are of low confidence.

Fig. 35 shows the evaporator fan motor power for the middle evaporator in the walk-in dairy cooler in Colchester, VT, for the period 20 April 2017 through 28 August 2017. The incumbent evaporator fan motors were replaced with PMS fan motors on 7 June 2017.

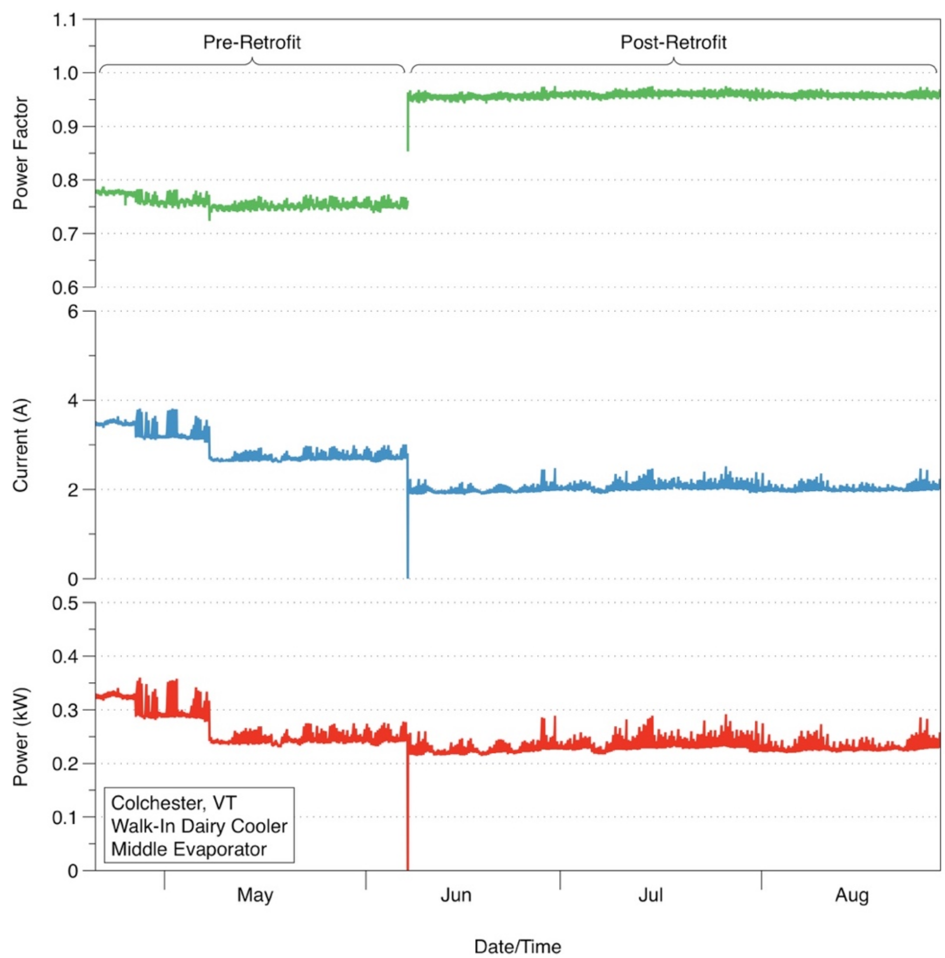

Fig. 35. Pre- and post-retrofit evaporator fan power, current and power factor for the middle evaporator in the walk-in dairy cooler, Colchester, VT.

It can be seen from Fig. 35 that the power of the incumbent evaporator fan motors decreased during the period 20 April to 7 June in three distinct steps. The initial fan motor power was approximately

325 W, then decreased to approximately 290 W, and then finally dropped to an average value of 246 W. The exact cause of this behavior is unknown.

As previously noted, it was intended that the evaporator coils would be cleaned prior to the fan motor performance evaluation. Perhaps the middle evaporator coil was cleaned around 30 April 2017, as indicated by the slight drop in evaporator fan power shown in Fig. 35. This decrease in power consumption around 30 April 2017 is consistent with that seen in left evaporator (discussed above). The cause of the further decrease in power occurring on 7 May 2017 is unknown. Perhaps motor failure occurred at this time, which further reduced the incumbent fan motor power.

The average PMS fan motor power for the period from 7 June 2017 to 28 August 2017 was 233 W. Assuming that the incumbent evaporator fan motor power of the middle evaporator is approximately 246 W, and similarly that the PMS evaporator fan motor power is approximately 233 W, the PMS motors are shown to use 5.3% less power than the incumbent motors. If indeed one or more incumbent fan motors failed on 7 May 2017, and assuming that the incumbent fan motor power was on the order of 290 W, then the power savings of the PMS motors would be approximately 20%. However, due to the anomalies in the data, these results are of low confidence.

Fig. 36 shows the evaporator fan motor power for the right evaporator in the walk-in dairy cooler in Colchester, VT, for the period 20 April 2017 through 28 August 2017. The incumbent evaporator fan motors were replaced with PMS motors on 7 June 2017.

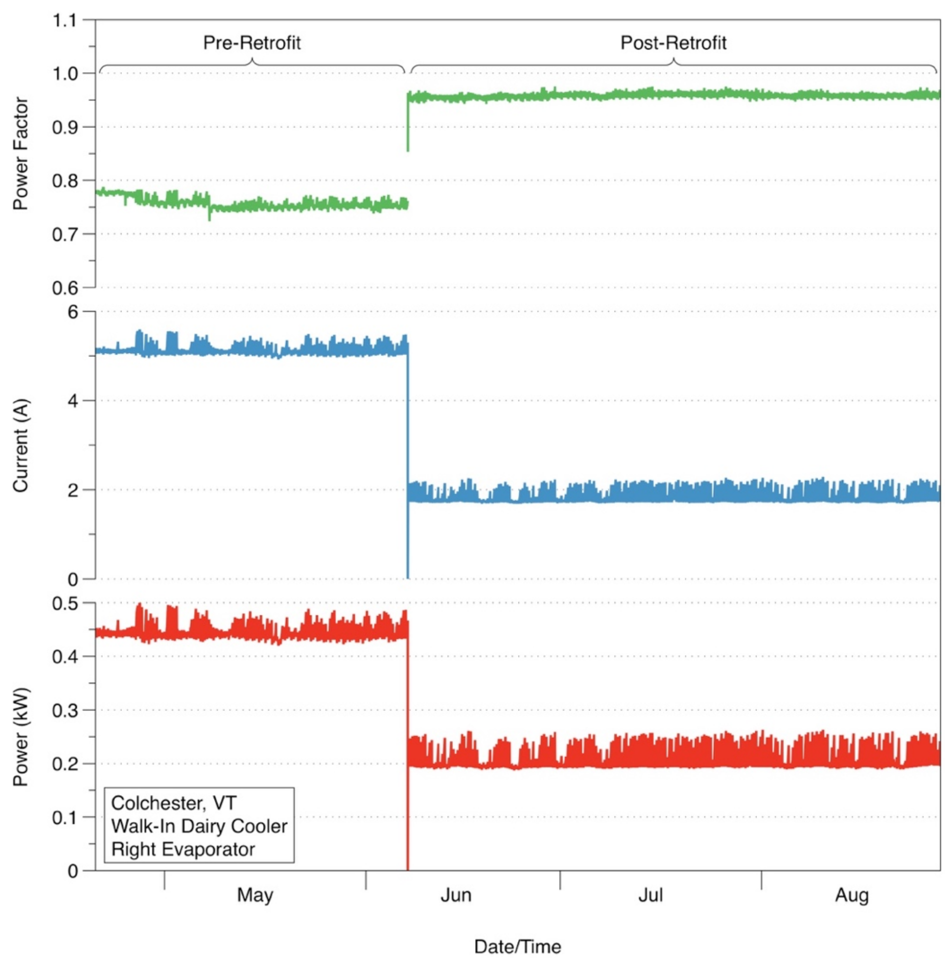

Fig. 36. Pre- and post-retrofit evaporator fan power, current and power factor for the right evaporator in the walk-in dairy cooler, Colchester, VT.

The average power of the incumbent evaporator fan motors was 447 W for the period 20 April 2017 through 7 June 2017. In addition, the average power of the PMS fan motors was 209 W for the period 7 June 2017 through 28 August 2017. Thus, the PMS motors used on average 53.2% less power than the incumbent motors.

The variability and anomalies in the walk-in cooler data from the Colchester, VT, store, makes it difficult to draw specific conclusions regarding the energy savings potential of retrofitting PMS fan motors in walk-in cooler evaporators.

4.2.2.4 Walk-In Freezer - Colchester, VT Supermarket

As shown in Table 12, the walk-in freezer at the Colchester, VT, supermarket, contained two evaporators, which will be designated as the left and right evaporators in the discussion below. Each of these evaporator coils contained five evaporator fan motors.

Fig. 37 shows the evaporator fan motor power for the left evaporator in the walk-in freezer of the Colchester, VT, store, for the period 20 April 2017 through 28 August 2017. The incumbent evaporator fan motors were replaced with PMS motors on 7 June 2017. A significant drop in fan power is noted following the installation of the PMS evaporator fan motors.

As shown in Fig. 37, the power consumption of the incumbent evaporator fan motors remained relatively consistent during the pre-retrofit period. During the post-retrofit period, a slight drop in PMS fan power consumption was noticed on 25 June 2017, while a slight increase in power occurred on 25 July, and the power remained at this level for the remainder of the data collection. The reasons for the step changes in evaporator fan power exhibited during the post-retrofit period are unknown. Due to the variability in the post-retrofit fan power data, no attempt was made to quantify the energy savings due to retrofitting the incumbent fan motors with PMS fan motors for the left evaporator.

As previously noted, it was intended that the evaporator coils would be cleaned prior to the fan motor performance evaluation. Since no significant decrease in fan motor power was noted during the pre-retrofit data collection, it would appear that the left evaporator coil was not cleaned.

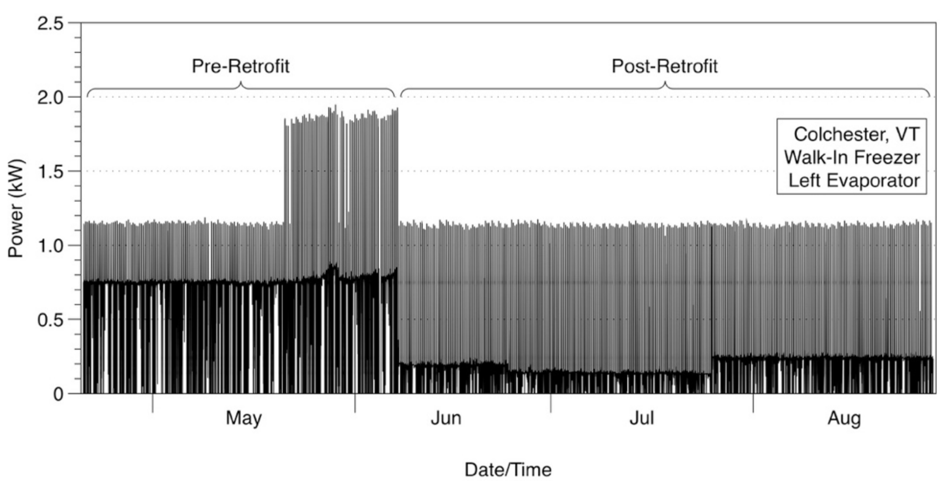

Fig. 37. Pre- and post-retrofit evaporator fan power for the left evaporator in the walk-in freezer, Colchester, VT.

Fig. 38 shows the evaporator fan motor power for the right evaporator in the walk-in freezer of the Colchester, VT, store, for the period 20 April 2017 through 28 August 2017. The incumbent evaporator fan motors were replaced with PMS motors on 7 June 2017. A dramatic drop in fan power is noted following the installation of the PMS evaporator fan motors. Furthermore, evaporator fan power appears to be erratic during the post-retrofit period, and the cause of this erratic behavior during the post-retrofit period is unknown. Again, due to the variability in the post-retrofit fan power data, no attempt was made to quantify the energy savings due to retrofitting the incumbent fan motors with PMS fan motors for the right evaporator.

As previously noted, it was intended that the evaporator coils would be cleaned prior to the fan motor performance evaluation. Since no significant decrease in fan motor power was noted during the pre-retrofit data collection, it would appear that the right evaporator coil was not cleaned.

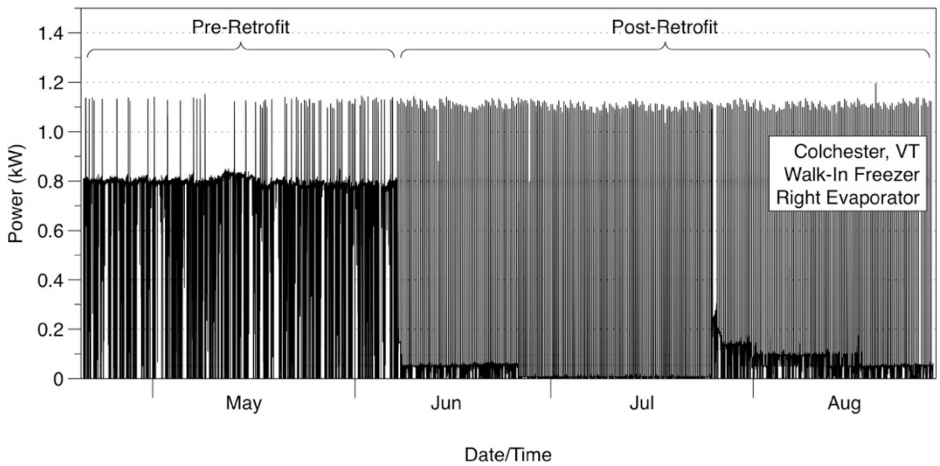

Fig. 38. Pre- and post-retrofit evaporator fan power for the right evaporator in the walk-in freezer, Colchester, VT.

The variability and anomalies in the walk-in freezer data from the Colchester, VT, store, particularly during the post-retrofit period, makes it difficult to draw conclusions regarding the energy savings potential of retrofitting PMS fan motors in walk-in freezer evaporators. The data collected during the walk-in evaporator fan motor study was not regularly monitored during collection, and thus, the anomalies in the data were only detected after the pre- and post-retrofit study was completed. Hence, it is not possible to determine the cause of the anomalies or account for the anomalies in the analysis of the data.

4.2.3 Summary of Walk-In Evaporator Fan Motor Evaluation

The data collected from the Burlington, VT store, indicates that a significant energy savings is possible when retrofitting incumbent walk-in cooler and freezer evaporator fan motors to PMS motors. A 61% decrease in fan motor power was measured when retrofitting existing evaporator fan motors with PMS motors in the walk-in cooler. In addition, a 48% decrease in fan motor power was measured when retrofitting existing evaporator fan motors with PMS motors in the walk-in freezer.

Unfortunately, the data collected from the Colchester, VT, store resulted in inconclusive results regarding the energy savings potential of retrofitting PMS motors in walk-in cooler/freezer evaporators. The data was not regularly monitored during collection, and on-site inspections did not occur, thus, the anomalies in the data were only detected after this pre- and post-retrofit study was completed. A lesson-learned from this would be to check the data regularly, and if anomalies exist, determine their cause and take corrective action.

4.3 WHOLE STORE EVAPORATOR FAN MOTOR RETROFITS

The culmination of the field evaluation of fan motor technologies was a whole-store retrofit conducted at a supermarket located in Dublin, OH, within the Columbus metropolitan area. Pre- and post-retrofit measurement of evaporator fan motor power in medium- and low-temperature refrigerated display cases and walk-in coolers/freezers was performed. The measurement and verification plan for this whole store evaporator fan motor retrofit included provisions for measuring evaporator fan motor power, voltage, current, and power factor.

4.3.1 Field Test Site

One test site was selected at which to perform a whole-store evaporator fan motor retrofit; a supermarket located in Dublin, OH. A total of 22 display case line-ups on 22 separate electrical circuits, and 16 walk-in coolers/freezers, on 20 separate electrical circuits were monitored during the whole-store evaporator fan motor retrofit. The four walk-ins with 230V motors required two electrical circuits each, which accounts for the four extra circuits. Table 17 provides details of the refrigerated display case line-ups studied, along with the type and number of evaporator fan motors in each display case line-up. A total of 185 8-in. diameter display case evaporator fan motors were included in the whole-store retrofit study. Table 18 shows the walk-in coolers/freezers included in the whole-store retrofit study, along with the type and number of evaporator fan motors in each walk-in. A total of 77 walk-in evaporator fan motors, with fan blade diameters of 10-in. or 12-in., were included in the study.

Table 17. Refrigerated display cases investigated in whole-store evaporator fan motor retrofit

Display case description	Case type	Number of evaporator fan motors	Motor type	Fan blade diameter (in.)
Frozen dessert	vertical closed glass door reach-in	4	SP	8
Frozen fruit, waffles, breakfast items	vertical closed glass door reach-in	15	SP	8
Ice cream and Ice	vertical closed glass door reach-in	15	SP	8
Frozen meat	vertical closed glass door reach-in	4	SP	8
Frozen seafood	vertical closed glass door reach-in	3	SP	8
Frozen pizza, appetizers, and vegetables	vertical closed glass door reach-in	8	SP	8
Frozen main courses	vertical closed glass door reach-in	9	SP	8
Frozen potatoes	vertical closed glass door reach-in	9	SP	8
Frozen food	vertical closed glass door reach-in	8	SP	8
Dairy: milk and yogurt	vertical open multi-deck	18	EC	8
Cheese: fresh, blocks and shredded	vertical open multi-deck	5	EC	8
Packaged meat, soup and sandwiches, wings and pizza	vertical open multi-deck	10	EC	8
Dairy: butter and tofu	vertical open multi-deck	4	EC	8
Dairy, juice and eggs	vertical open multi-deck	10	EC	8
Beverages	vertical open multi-deck	2	SP	8
Grab & go beverages	vertical open multi-deck	4	EC	8
Grab & go beverages	vertical open multi-deck	5	SP	8

Display case description	Case type	Number of evaporator fan motors	Motor type	Fan blade diameter (in.)
Beer	vertical open multi-deck	10	EC	8
Produce: salad greens	vertical open multi-deck	6	EC	8
Produce	vertical open multi-deck	12	EC	8
Wine	vertical open multi-deck	6	EC	8
Produce: prepared fruit and vegetables.	vertical open multi-deck	18	EC	8

Table 18. Walk-in coolers/freezers investigated in whole-store evaporator fan motor retrofit

Description	Number of evaporator fan motors	Motor type	Fan blade diameter (in.)
Salad cooler and organics room	3	PSC	10
Food preparation	6	PSC	12
Dairy cooler	9	PSC	12
Poultry preparation	4	PSC	10
Bakery cooler	3	PSC	12
Pastry cooler	3	PSC	10
Cheese cooler	3	PSC	12
Meat cooler	6	PSC	10
Seafood preparation	4	PSC	10
Produce cooler	6	PSC	10
Beverage cooler	3	PSC	10
Beer cave	4	EC	12
Produce preparation	6	PSC	10
Poultry cooler	4	PSC	10
Freezer	10	PSC	12
Seafood freezer	3	PSC	12

Each display case line-up or walk-in cooler/freezer had a dedicated electrical circuit breaker that supplied electrical power to the evaporator fans in that display case line-up or walk-in. In this study, the evaporator fan motor electric power measurements were made at the circuit breaker level. Thus, the electrical power measurements represent the motor power, voltage, current, and power factor for all the fans operating on a given circuit. A total of 22 display case evaporator fan circuits, representing 185 fan motors, and 20 walk-in evaporator fan circuits, representing a total of 77 motors, were monitored and recorded. By motor type, 103 EC motors and 82 shaded pole motors were replaced in the monitored refrigerated display cases, and 73 PSC motors and 4 EC motors were replaced in the monitored walk-ins. Measured quantities for each electrical circuit included fan motor power, voltage, current, and power factor, and these quantities were measured every 30 seconds and then averaged and recorded every two minutes. Table 19 lists the specifications of the instrumentation used during the whole store evaporator fan motor retrofit portion of this study.

Table 19. Instrumentation specifications for whole store evaluation of evaporator fan motors

Instrument	Measured quantity	Instrument range	Accuracy
Power Meter	Fan power, current, voltage and power factor	Power: 0 to 600 W Current: 0 to 25 A Voltage: 90 to 600 V	Power: 0.2% Current: 0.4% Voltage: 0.4%

During the installation of PMS evaporator fan motors, since refrigeration effect depends upon airflow rate, care was taken to meet or exceed the airflow rate of the incumbent fans by using appropriately pitched fan blades on the PMS motors. Details of the procedure to match airflow rate between incumbent and PMS fan motor assemblies is provided in Section 3.2.2.3. In some instances, the airflow with the replacement PMS fan motor assemblies was greater than the original airflow. Thus, the electrical energy savings were reduced because the replacement PMS fans were moving a greater quantity of air than the original fans. Greater electrical energy savings could be achieved by more closely matching the air flow rates between the PMS fan motor assemblies and the incumbent fan motor assemblies. Furthermore, to aid in the installation of the PMS evaporator fan motors in the display cases, the entire incumbent fan assembly, consisting of the fan motor, blade and mounting basket, were replaced with a similar PMS fan assembly (see Fig. 39). The incumbent baskets and blades were not reused, which reduced installation time and cost.

Fig. 39. Evaporator fan motor assembly, consisting of the fan motor, blade and mounting basket.

4.3.2 Field Evaluation Results and Discussion

4.3.2.1 Energy Savings

Three monitored display case fan circuits ('Frozen dessert', 'Frozen meat', and 'Frozen seafood') were found to not only supply power to the evaporator fan motors, but also to the display case lighting. Thus, during the evaporator fan motor retrofit, the current draw and power consumption were noted for these three circuits while all of the fan motors were out of the cases, thereby giving the current draw and power consumption of the lighting. The recorded data for current draw and power consumption were then adjusted accordingly to remove the contribution attributed to the lighting. It was also noted that during the fan motor retrofit, one incumbent fan motor was not working in each of the following three circuits: 'Produce: salad greens', 'Produce', and 'Produce: prepared fruit and vegetables'. The reported incumbent "per motor" power data was adjusted to account for these non-functioning fan motors.

Table 20 summarizes the evaporator fan motor current, real power, apparent power and power factor for the display case line-ups that were monitored at the Dublin, OH supermarket. The data reported in Table 20 (pre- and post-retrofit) has been normalized on a "per motor" basis. In addition, Table 21 compares the average performance of the PMS, SP and EC fan motors. From Table 21, it can be seen that on average, the PMS evaporator fan motors consumed 60% less current and 50% less real power compared to the SP evaporator fan motors. In addition, the power factor of the PMS evaporator fan motors was 30% higher than that of the SP evaporator fan motors. It is possible that greater electrical energy savings could have been achieved if the PMS fan motor airflow more closely matched the original SP fan motor airflow. Also shown in Table 21, compared to the EC evaporator fan motors, the PMS fan motors consumed 54% less current and 38% less real power on average. The power factor of the PMS fan motors was 33% greater than that of the EC fan motors. In total, following the retrofit of the 185 display case evaporator fan motors, the current supplied to the display case evaporator fan motors was reduced by 37 A and the real power was reduced by 2480 W.

Table 22 summarizes the evaporator fan motor current, real power, apparent power and power factor for the walk-in coolers/freezers that were monitored at the Dublin, OH supermarket. The data reported in Table 22 (pre- and post-retrofit) has been normalized on a "per motor" basis. In addition, Table 23 compares the average performance of the PMS, PSC and EC fan motors. From Table 23, it can be seen that on average, the PMS evaporator fan motors consumed 43% less current and 49% less real power compared to the PSC evaporator fan motors. The power factor of the PMS evaporator fan motors was 10% lower than that of the PSC evaporator fan motors. Compared to the EC evaporator fan motors, the PMS fan motors consumed 43% less current and 47% less real power on average. The power factor of the PMS fan motors was 6% greater than that of the EC fan motors. In total, following the retrofit of the 77 walk-in cooler/freezer evaporator fan motors, the current supplied to the walk-in cooler/freezer evaporator fan motors was reduced by 18 A and the real power was reduced by 2230 W.

Overall for the Dublin, OH supermarket, the current supplied to all monitored evaporator fan motors was reduced by 55 A (a 52% reduction), the real power was reduced by 4710 W (a 46% reduction) and the apparent power was reduced by 7150 VA (a 51% reduction) following the retrofit of the 262 evaporator fan motors that were monitored.

Assuming that evaporator fan motors operate 8760 hours per year, it is estimated that the total annual energy consumption of all the monitored fan motors will be reduced by 41,300 kWh as a result of the evaporator fan motor retrofit. Furthermore, assuming an energy cost of $0.1058 per kWh (EIA 2015), the reduction in energy consumption correlates to a total annual cost savings of $4,370 for all the monitored motors. In addition, given that motor efficiency losses are released as heat, the higher efficiency PMS motors will result in a decreased refrigeration load and a corresponding incremental decrease in overall refrigeration system energy consumption (Fricke and Becker 2015).

Table 20. Summary of refrigerated display case evaporator fan motor energy performance – full store retrofit

Display case description	Pre-retrofit (per motor)				Post-retrofit (per motor)				Difference (%)			
	Current (A)	Real power (W)	Apparent power (VA)	Power factor	Current (A)	Real power (W)	Apparent power (VA)	Power factor	Current	Real power	Apparent power	Power factor
SPM incumbents												
Frozen dessert	0.303	32.4	37.6		0.143	17.1	19.3		-53.0	-47.2	-48.8	
Frozen fruit, waffles, breakfast items	0.429	34.2	51.7	0.660	0.161	17.1	19.5	0.877	-62.6	-50.1	-62.4	32.8
Ice cream and ice	0.439	35.4	53.2	0.666	0.168	18.0	20.4	0.881	-61.8	-49.3	-61.7	32.3
Frozen meat	0.283	29.3	34.6		0.141	16.6	18.8		-50.3	-43.3	-45.7	
Frozen seafood	0.292	29.8	35.5		0.141	15.4	17.9		-51.6	-48.3	-49.6	
Frozen pizza, appetizers, and vegetables	0.434	34.5	52.3	0.657	0.174	18.4	21.1	0.872	-60.0	-46.8	-59.7	32.8
Frozen main courses	0.429	34.2	51.6	0.663	0.165	17.2	19.9	0.861	-61.5	-49.9	-61.4	29.9
Frozen potatoes	0.428	34.3	51.8	0.663	0.159	17.0	19.3	0.881	-62.9	-50.4	-62.7	32.8
Frozen prepared foods	0.440	34.7	53.3	0.652	0.171	18.2	20.9	0.874	-61.0	-47.4	-60.8	34.1
Beverages	0.651	51.4	79.0	0.650	0.138	14.6	16.8	0.871	-78.8	-71.5	-78.7	34.0
Grab & go beverages	0.325	30.9	39.2	0.787	0.128	13.2	15.5	0.855	-60.7	-57.1	-60.6	8.7
ECM Incumbents												
Dairy: milk and yogurt	0.355	36.1	43.0	0.839	0.140	14.9	17.0	0.876	-60.7	-58.8	-60.6	4.5
Cheese: fresh, blocks and shredded	0.324	23.6	39.3	0.602	0.133	13.9	16.1	0.861	-59.1	-41.3	-59.0	43.0
Packaged meat, soup and sandwiches, wings and pizza	0.344	32.3	41.5	0.779	0.131	13.6	15.8	0.861	-62.0	-57.8	-61.8	10.5

Display case description	Pre-retrofit (per motor)				Post-retrofit (per motor)				Difference (%)			
	Current (A)	**Real power (W)**	**Apparent power (VA)**	**Power factor**	**Current (A)**	**Real power (W)**	**Apparent power (VA)**	**Power factor**	**Current**	**Real power**	**Apparent power**	**Power factor**
Diary: butter and tofu	0.306	22.0	37.1	0.596	0.129	13.6	15.7	0.864	-57.8	-38.4	-57.7	44.9
Dairy, juice and eggs	0.269	22.5	32.5	0.691	0.110	11.6	13.3	0.872	-59.3	-48.4	-59.1	26.2
Grab & go beverages	0.306	21.8	37.0	0.590	0.126	13.1	15.3	0.859	-58.8	-39.8	-58.7	45.6
Beer	0.293	20.2	35.3	0.572	0.122	12.9	14.7	0.876	-58.5	-36.0	-58.2	53.1
Produce: salad greens	0.302	22.9	36.3	0.631	0.145	15.1	17.5	0.863	-51.8	-33.9	-51.7	36.8
Produce	0.297	24.3	36.0	0.673	0.159	17.2	19.3	0.891	-46.5	-28.9	-46.2	32.4
Wine	0.309	22.3	37.2	0.599	0.132	14.0	16.0	0.872	-57.3	-37.4	-57.0	45.5
Produce: Prepared fruit and vegetables	0.271	25.1	32.6	0.768	0.175	19.5	21.1	0.927	-35.6	-22.1	-35.5	20.7

Table 21. Average performance of display case evaporator fan motors PMS versus SP and EC for the whole-store retrofit

Performance indicator	PMS vs. SP	PMS vs. EC
Average change: Current (%)	-60.4	-53.5
Average change: Real power (%)	-50.1	-38.1
Average change: Apparent power (%)	-59.3	-53.4
Average change: Power factor (%)	29.7	33.0

Table 22. Summary of walk-in cooler/freezer evaporator fan motor energy performance – full store retrofit

Walk-in description	Pre-retrofit (per motor)				Post-retrofit (per motor)				Difference (%)			
	Current (A)	Real power (W)	Apparent power (VA)	Power factor	Current (A)	Real power (W)	Apparent power (VA)	Power factor	Current	Real power	Apparent power	Power factor
PSCM Incumbents												
Salad cooler and organics room	0.66	54.7	79.8	0.69	0.33	22.2	39.4	0.57	-50.9	-59.4	-50.6	-16.4
Food preparation	0.66	68.7	80.5	0.85	0.40	43.9	48.3	0.91	-40.2	-36.1	-40.0	6.5
Dairy cooler	0.70	77.2	85.2	0.91	0.50	57.7	60.7	0.95	-29.0	-25.2	-28.7	4.9
Poultry preparation	0.58	50.6	70.5	0.72	0.28	21.2	33.6	0.63	-52.5	-58.0	-52.3	-12.2
Bakery cooler	0.69	71.3	83.7	0.85	0.40	44.5	48.5	0.92	-42.2	-37.7	-42.0	7.6
Pastry cooler	0.60	48.3	72.1	0.67	0.30	21.9	36.1	0.61	-50.2	-54.7	-49.9	-9.4
Cheese cooler	0.69	75.7	84.0	0.90	0.43	48.6	52.6	0.92	-37.6	-35.8	-37.3	2.4
Meat cooler	0.14	42.9	51.2	0.83	0.09	21.0	33.4	0.62	-34.7	-51.1	-34.7	-25.2
Seafood preparation	0.60	56.7	73.0	0.78	0.30	22.6	36.9	0.61	-49.7	-60.2	-49.4	-21.0
Produce cooler	0.65	62.5	78.6	0.80	0.29	20.8	35.3	0.60	-55.5	-66.7	-55.2	-24.7
Beverage cooler	0.42	48.6	49.9	0.97	0.26	20.8	31.2	0.67	-37.7	-57.3	-37.6	-31.6
Produce preparation	0.59	45.8	71.2	0.64	0.26	20.2	31.2	0.65	-56.4	-55.8	-56.1	1.1
Poultry cooler	0.14	42.5	51.6	0.82	0.10	21.4	35.5	0.60	-31.2	-49.6	-31.2	-26.9
Freezer	0.30	77.2	107.2	0.72	0.14	39.9	51.3	0.78	-52.2	-48.3	-52.2	8.8
Seafood freezer	0.22	66.6	78.7	0.84	0.16	45.3	57.9	0.78	-26.4	-32.0	-26.4	-8.0
ECM Incumbents												
Beer cave	1.05	94.5	125.7	0.75	0.59	50.5	71.4	0.71	-43.3	-46.5	-43.1	-5.9

Table 23. Average performance of walk-in cooler/freezer evaporator fan motors PMS versus PSC and EC for the whole-store retrofit

Performance indicator	PMS vs. PSC	PMS vs. EC
Average change: Current (%)	-43.1%	-43.3%
Average change: Real power (%)	-48.5%	-46.5%
Average change: Apparent power (%)	-42.9%	-43.1%
Average change: Power factor (%)	-9.6%	-5.9%

4.3.2.2 Simple Payback Period

Based on information from the PMS evaporator fan motor manufacturer, the installed cost of the PMS display case evaporator fan motor is estimated to be $85 and the installed cost of the PMS walk-in cooler/freezer evaporator fan motor is estimated to be $115. The total installed cost of the replaced and monitored display case and walk-in evaporator fan motors is estimated to be $15,725 and $8,855, respectively, for a total installed cost of $24,580. Based on the estimated annual energy cost savings ($4,370), this represents a simple payback period of 5.6 years.

Utility incentives may be applicable and could be applied to reduce the simple payback period. For instance, if a $25 rebate is offered for installing the display case fan motors while a $50 rebate is offered for installing the walk-in fan motors, the total installed cost would be $16,105 and the simple payback period would be reduced to 3.7 years.

Installation of more efficient evaporator fan motors will reduce the heat load imposed on the display cases and the walk-in coolers/freezers. Assuming all the energy consumed by the evaporator fan motors is dissipated as heat within the display cases and walk-ins, and further assuming an average coefficient of performance (COP) for the refrigeration system of 2.5, the compressor energy consumption could be reduced by up to 16,500 kWh per year, with a corresponding annual compressor energy cost savings of $1,750. Factoring in both the utility incentives mentioned above and the estimated compressor energy consumption reduction, the simple payback period is reduced to 2.6 years.

5. POTENTIAL SITE AND SOURCE ENERGY SAVINGS

Based on the results of the laboratory and field evaluations of evaporator fan motors, the potential site and source energy savings associated with retrofitting the existing installed base of 6–12 W and 38–50 W commercial refrigeration evaporator fan motors with PMS fan motors can be estimated.

5.1 SITE ENERGY SAVINGS

For purposes of comparison, a baseline must be established. This baseline includes performance characteristics for the current installed base of 6–12 W and 38–50 W evaporator fan motor types, as well as statistics regarding the installed base of 6–12 W and 38–50 W commercial refrigeration evaporator fan motors.

The characteristics of various types of evaporator fan motors are given in Table 24. The motor efficiencies and power factors of the shade-pole, PSC, EC and PMS motors were obtained from the dynamometer test data discussed in Section 3.1. Output power for the 6–12 W motors was assumed to be 12 W, while for the 38–50 W motors, output power was assumed to be 38 W. The input power was calculated from the assumed output power and the measured motor efficiency. It was assumed that all evaporator fan motors in commercial refrigeration equipment and beverage vending machines operated continuously for 8760 hours per year.

Table 24. Characteristics of 6–12 W and 38–50 W evaporator fan motors

Motor type	Motor efficiency (%)	Power factor	Output power (W)	Input power (W)
6–12 W motors				
Shaded-pole	26	0.64	12	47
EC	63	0.61	12	19
PMS	75	0.91	12	16
38–50 W motors				
PSC	50	0.97	38	76
EC	69	0.61	38	55
PMS	82	0.92	38	46

Table 25 provides details of the number of installed 6–12 W evaporator fan motors. Based on a survey of the installed base, it is estimated that there are approximately 15.8×10^6 6–12 W evaporator fan motors installed in commercial refrigeration equipment and beverage vending machines. Facility count information was obtained from Progressive Grocer (2015), the Association for Convenience and Fuel Retailing (NACS 2015), the National Restaurant Association (NRA 2015), IBIS World (2015) and Statistic Brain (2015), and the number of motors per facility was estimated based on discussions with industry partners.

Table 25. Installed base of 6–12 W evaporator fan motors

Facility type	Facility count	Motors per facility	Total motors installed	Total motors installed per facility type
Supermarkets (sales greater than $2 million)				7,158,555
Supermarket (conventional)[a]	26,487	225	5,959,575	
Supercenter (grocery and mass merchandise)[a]	4,150	175	726,250	
Supermarket (limited assortment)[a]	3,242	50	162,100	
Supermarket (natural/gourmet)[a]	3,144	70	220,080	
Warehouse grocery[a]	523	100	52,300	
Military commissary[a]	170	225	38,250	
Other Food Retail Formats				1,146,988
Conventional convenience store[b]	152,794	7	1,069,558	
Gas station/kiosk[a]	22,303	2	44,606	
Superette[a]	13,070	2	26,140	
Conventional club[a]	1,320	2	2,640	
Military commissary[a]	674	6	4,044	
Other Retailer Categories				653,256
Drug store[b]	41,799	8	334,392	
Dollar store[b]	26,572	12	318,864	
Restaurants/Bars				4,280,064
Restaurant[c]	1,000,000	4	4,000,000	
Bar/nightclub[d]	70,016	4	280,064	
Beverage Vending Machines[e]	2,598,400	1	2,598,400	2,598,400
TOTAL			**15,837,263**	

[a] Source: Progressive Grocer (2015).
[b] Source: NACS (2015).
[c] Source: NRA (2015).
[d] Source: IBIS World (2015).
[e] Source: Statistic Brain (2015).

Table 26 provides details of the number of installed 38–50 W evaporator fan motors. Based on a survey of the installed base, it is estimated that there are approximately 14.4×10^6 38–50 W evaporator fan motors installed in commercial refrigeration equipment.

Table 26. Installed base of 38–50 W evaporator fan motors

Facility type	Facility count	Motors per facility	Total motors installed	Total motors installed per facility type
Supermarkets (sales greater than $2 million)				3,104,776
Supermarket (conventional)[a]	26,487	96	2,542,752	
Supercenter (grocery and mass merchandise)[a]	4,150	64	265,600	
Supermarket (limited assortment)[a]	3,242	36	116,712	
Supermarket (natural/gourmet)[a]	3,144	36	113,184	
Warehouse grocery[a]	523	96	50,208	
Military commissary[a]	170	96	16,320	
Other Food Retail Formats				1,521,288
Conventional convenience store[b]	152,794	8	1,222,352	
Gas station/kiosk[a]	22,303	8	178,424	
Superette[a]	13,070	8	104,560	
Conventional club[a]	1,320	8	10,560	
Military commissary[a]	674	8	5,392	
Other Retailer Categories				820,452
Drug store[b]	41,799	12	501,588	
Dollar store[b]	26,572	12	318,864	
Restaurants/Bars				8,903,656
Restaurant[c]	1,000,000	4	8,000,000	
Bar/nightclub[d]	70,016	4	560,128	
Liquor store	42,941	8	343,528	
TOTAL			**14,350,172**	

[a] Source: Progressive Grocer (2015).
[b] Source: NACS (2015).
[c] Source: NRA (2015).
[d] Source: IBIS World (2015).

Table 27 shows the assumed distribution of motor types for the existing installed base of evaporator fan motors for each facility type listed in Table 25 and Table 26. This assumed distribution was estimated based on discussions with industry partners.

Table 27 also shows the total annual site electrical energy consumption of these fan motors which was calculated based upon the total number of installed motors of each type, the input power of each motor type and 8760 continuous hours of operation per year. As shown in Table 27 for the baseline case, it is estimated that 15.1×10^9 kWh (0.0514 quad) per year of site electricity is consumed by the existing installed base of 6–12 W and 38–50 W evaporator fan motors. Assuming the cost of electricity is 10.58 cents per kilowatt-hour (EIA 2015), this translates into nearly $1.6 billion. Also, assuming carbon dioxide equivalent emissions of 1.67 lb of CO_2 per kilowatt-hour of electricity delivered (Deru and Torcellini 2007), the CO_2 emissions associated with the currently installed base of evaporator fan motors is estimated to be 25.2×10^9 lb.

Table 27. Baseline distribution of 6–12 W and 38–50 W evaporator fan motors and total site energy consumption

Motor type by application	Percentage of installed base (%)	Total motors installed	Annual site electrical energy consumption (kWh/y)
Supermarkets			
6–12 W motors			
Shaded pole	65	4,653,061	1,915,758,172
EC	35	2,505,494	417,014,463
PMS	0		
38–50 W motors			
PSC	95	2,949,537	1,963,683,886
EC	5	155,239	74,794,054
PMS	0		
Other Food Retail Formats			
6–12 W motors			
Shaded pole	85	974,940	401,402,214
EC	15	172,048	28,635,702
PMS	0		
38–50 W motors			
PSC	95	1,445,224	962,172,064
EC	5	76,064	36,647,828
PMS	0		
Other Retail Categories			
6–12 W motors			
Shaded pole	75	489,942	201,718,920
EC	25	163,314	27,181,982
PMS	0		
38–50 W motors			
PSC	95	779,429	518,912,917
EC	5	41,023	19,764,689
PMS	0		
Restaurants and Bars			
6–12 W motors			
Shaded pole	90	3,852,058	1,585,969,155
EC	10	428,006	71,237,385
PMS	0		
38–50 W motors			
PSC	95	8,458,473	5,631,313,118
EC	5	445,183	214,489,073
PMS	0		
Beverage Vending Machines			
6–12 W motors			
Shaded pole	90	2,338,560	962,831,923
EC	10	259,840	43,247,770
PMS	0		
TOTAL			**15,076,775,315**
			(0.0514 Quads)
		Energy Cost:	$1,595,122,828
		CO_2 Emissions:	25,178,214,776 lb

As shown in Table 28, if all 30.2×10^6 currently installed 6–12 W and 38–50 W evaporator fan motors were retrofitted with PMS fan motors, the total site electricity consumption would be estimated at 8.0×10^9 kWh per year (0.0273 quad/year). Recall that the electrical energy consumption of the existing installed base of evaporator fan motors is 15.1×10^9 kWh (0.0514 quad) per year. Thus, the total retrofit of all evaporator fan motors represents a site energy savings of approximately 7.1×10^9 kWh/year (0.0241 quad/year) or 47%, resulting in an annual cost savings of $748 million compared with the base case. Furthermore, PMS motors are estimated to reduce the annual CO_2 equivalent emissions by approximately 11.8×10^9 lb compared with the baseline.

Table 28. Retrofit distribution of 6–12 W and 38–50 W evaporator fan motors and total site energy consumption

Motor type by application	Percentage of installed base (%)	Total motors installed	Annual site electrical energy consumption (kWh/y)
Supermarkets			
6–12 W motors			
Shaded pole	0		
EC	0		
PMS	100	7,158,555	1,003,343,069
38–50 W motors			
PSC	0		
EC	0		
PMS	100	3,104,776	1,251,100,537
Other Food Retail Formats			
6–12 W motors			
Shaded pole	0		
EC	0		
PMS	100	1,146,988	160,761,838
38–50 W motors			
PSC	0		
EC	0		
PMS	100	1,521,288	613,018,212
Other Retail Categories			
6–12 W motors			
Shaded pole	0		
EC	0		
PMS	100	653,256	91,560,361
38–50 W motors			
PSC	0		
EC	0		
PMS	100	820,452	330,609,338
Restaurants and Bars			
6–12 W motors			
Shaded pole	0		
EC	0		
PMS	100	4,280,064	599,893,770
38–50 W motors			
PSC	0		
EC	0		
PMS	100	8,903,656	3,587,817,222
Beverage Vending Machines			
6–12 W motors			
Shaded pole	0		

Motor type by application	Percentage of installed base (%)	Total motors installed	Annual site electrical energy consumption (kWh/y)
EC	0		
PMS	100	2,598,400	364,191,744
TOTAL			**8,002,296,091**
			(0.0273 Quads)
		Energy Cost:	$846,642,926
		CO_2 Emissions:	13,363,834,472 lb

5.2 SOURCE ENERGY SAVINGS

Based on the site energy analysis presented, the potential source energy savings associated with retrofitting existing 6–12 W and 38–50 W commercial refrigeration evaporator fan motors with PMS fan motors can be estimated. Recall that "source energy" refers to the sum of the energy consumed at the site (site energy) plus the energy required to extract, convert, and transmit that energy to the site, whereas "site energy" refers to the energy directly consumed at the site (Deru and Torcellini 2007). Furthermore, DOE estimates that the conversion from site to source electric energy is 3.16 units of source energy per unit of site energy (DOE 2011).

The site and source energy consumption and potential energy savings for the PMS fan motor retrofit scenario discussed above, are given in Table 29. This table gives the site and source energy consumption for the baseline case of installed commercial refrigeration evaporator fan motors, as well as the site and source energy consumption for a retrofit consisting entirely of PMS fan motors. The third column of Table 29 gives the annual source energy savings of 0.076 quad/year for the PMS evaporator fan motor retrofit discussed above.

Recall from the discussion in the Introduction that the DOE BTO estimates that the primary or source energy consumption of electric motors in central commercial refrigeration and beverage vending machines is 96×10^9 kWh for central commercial refrigeration and 52×10^9 kWh for beverage vending machines (NCI 2013). Thus, the source energy consumption of all electric motors in central commercial refrigeration and beverage vending machines is approximately 148×10^9 kWh per year, or 0.50 quad per year (NCI 2013). Therefore, if all currently installed 6–12 W and 38–50 W evaporator fan motors were replaced with PMS fan motors, the total source or primary energy attributed to all electric motors in central commercial refrigeration and beverage vending machines could be reduced by 0.076 quad/year resulting in a source energy consumption of 0.42 quad/year, representing a savings of 16%.

Table 29. Annual source energy consumption and savings for baseline and PMS fan motors

Installed base	Annual site electrical energy consumption (kWh/year)	Annual source energy consumption (quad/year)	Annual source energy savings vs. baseline (quad/year)
Baseline fan motors	15.1×10^9	0.163	
PMS fan motors	8.0×10^9	0.086	0.076

6. EFFECTS OF FAN MOTOR POWER FACTOR

The analysis presented in Section 5.1 estimates only the "real" energy consumed at the site by the various types of evaporator fan motors. However, given that PMS fan motors exhibit a significantly higher power factor than EC and shaded-pole or PSC motors, it is expected that, through the implementation of PMS motors, utility companies will realize additional "apparent" energy savings at their power plants beyond the "real" energy savings at the sites. This additional apparent energy savings at the power plant should encourage utility companies to offer incentive programs for retrofitting PMS motors in place of EC and shaded-pole or PSC motors.

The "real" power, P, consumed by evaporator fan motors—that is, the power that produces useful work—is the power that would be measured at the site by a utility power meter. The analysis presented in Section 5.1 uses this "real" power to determine the total site energy consumption due to operation of evaporator fan motors. However, electric motors also require reactive power, Q, to operate. The reactive power does not do any useful work, but it provides the magnetic field required to produce rotation of the motor's rotor. Reactive power is typically not measured at the site; however, the power plant must provide the reactive power, in addition to the real power, for the motor to operate.

In a purely resistive AC circuit, voltage and current are perfectly in phase, and there is no reactive power. All the power consumed by the resistive load is real power. On the other hand, AC circuits with inductors and/or capacitors exhibit a phase difference between the voltage and the current; thus both real and reactive power are required by the load. The vector sum of the real power, P, and the reactive power, Q, is called the apparent power, S. Thus, the power plant must supply this apparent power for the motor to operate. The ratio between real power and apparent power is defined as the power factor, PF. Real power, reactive power, apparent power and power factor are related as follows:

$$S^2 = P^2 + Q^2$$
$$PF = \frac{P}{S} = \frac{P}{V_{rms} I_{rms}} \tag{1}$$

where V_{rms} is the root-mean-square voltage and I_{rms} is the root-mean-square current.

For a resistive load (such as an electric heating element or an incandescent light bulb), the real and apparent power are equal since there is no reactive power; thus, the power factor is one. However, for an inductive load (such as an induction motor), both real power and reactive power are required; therefore, real power is less than apparent power and the resulting power factor is less than one.

For the same real power output, a load with a low power factor requires more current than a load with a high power factor. Thus, PMS fan motors, with their high power factor, will consume less current than motors with a lower power factor. The lower current draw of the PMS motors means reduced generation and transmission costs for the utility company.

The reduction in apparent power generation at the power plant due to evaporator fan motor retrofits can be estimated using the power factors of the existing 6–12 W and 38–50 W commercial refrigeration evaporator fan motors and the PMS fan motors given in Table 24.

As discussed in Section 5.1 and shown in Table 27, for the baseline case of all shaded-pole, PSC and EC motors, the total site electricity consumption is estimated to be 15.1×10^9 kWh per year. Dividing by 8760 hours per year, the instantaneous real power required is 1.72×10^9 W. From the data given in Table 24 and Table 27, the weighted average power factor for the installed base of 6–12 W and 38–50 W shaded-pole, PSC and EC motors is calculated to be 0.78. Dividing the instantaneous real power by this power factor results in an instantaneous apparent power of 2.19×10^9 VA. The current required to supply this instantaneous apparent power can be calculated as follows:

$$I_{rms} = \frac{P}{V_{rms}PF} = \frac{S}{V_{rms}} \,. \tag{2}$$

Assuming V_{rms} = 120 V, electric utility companies would need to supply 18.3×10^6 A of current to the grid to provide the instantaneous apparent power required by the baseline case of all shaded-pole, PSC and EC motors.

In contrast, as discussed in Section 5.1, if all currently installed fan motors were retrofitted with PMS fan motors, the total site electricity consumption would be estimated at 8.0×10^9 kWh per year. Dividing by 8760 hours per year, the instantaneous real power required would be 0.91×10^9 W. As shown in Table 24 and Table 28, the weighted average power factor for the PMS motor is 0.91. Dividing the instantaneous real power by this power factor results in an instantaneous apparent power of 1.0×10^9 VA. To provide this instantaneous apparent power required by the PMS motors, electric utility companies would need to supply 8.3×10^6 A of current to the grid.

Thus, comparing the baseline case of all shaded-pole, PSC and EC motors with an installed base of PMS motors, it can be seen that utilities would be required to supply 54% less apparent power and 54% less current for PMS motors compared with the baseline combination of shaded-pole, PSC and EC motors. This would amount to significant savings for the utilities. Additional savings could be possible from a reduction in transmission line investments or related maintenance due to the lower levels of delivered current.

7. CONCLUSIONS

This report provided background information on various fractional-horsepower electric motor technologies used for evaporator fan applications in commercial refrigeration and summarized data from a DOE-sponsored evaporator fan motor laboratory and field demonstration project. This report also extrapolated that data to project the potential economic and environmental benefits resulting from upgrading the current installed base of commercial refrigeration evaporator fan motors to PMS motors.

7.1 EVAPORATOR FAN MOTOR TECHNOLOGIES

The theory of operation of various evaporator fan motor technologies was discussed, including shaded-pole (SP), permanent split capacitor (PSC), electronically commutated (EC) and permanent magnet synchronous (PMS) motors. The operation of all electric motors is based on the interaction between a field magnet and a magnetic rotor. The different types of motors result from the manner in which the rotating magnetic fields are generated. One of the most significant differences among various types of single-phase induction motors is the way they handle start-up (NCI/PNNL 2011). The efficiencies of these various motor technologies were discussed and related to their theory of operation. The DOE reports that for commercial refrigeration evaporator fan motor applications, EC motors are 66% efficient, PSC motors are 29% efficient and SP motors are 20% efficient.

7.2 LABORATORY EVALUATION OF FAN MOTOR TECHNOLOGIES

Laboratory evaluation of evaporator fan motor technologies was performed to quantify and compare the performance of shaded-pole, PSC, EC, and PMS evaporator fan motors in a controlled environment, so as to minimize the influence of external factors and anomalies. The laboratory evaluation included dynamometer testing of the fan motors and airflow testing of the motor/fan assemblies.

7.2.1 Dynamometer Testing of Fan Motor Technologies

Dynamometer testing of shaded-pole, PSC, EC, and PMS evaporator fan motors was performed to determine the power output, power factor and efficiency of the various motor technologies as the load on the motor was incrementally increased. The dynamometer test setup, procedure and results were discussed. It was found that the 6–12 W PMS motor exhibited a peak efficiency of 75% with a power factor of approximately 0.9 at a power output of 11 W. Various 6–12 W EC motors were tested and the peak efficiency of these EC motors ranged from about 62% to 67% with power factors ranging from 0.58 to 0.66, at a power output of 10 to 14 W. One 6–12 W shaded pole motor was evaluated and it was found that its peak efficiency was 27% with a power factor of 0.66 at a power output of 13 W.

It was found that a 38–50 W PMS motor exhibited a peak efficiency of 82% with a power factor of approximately 0.9 at a power output of 35 W. Various 38–50 W EC motors were tested and the peak efficiency of these EC motors ranged from about 64% to 73% with power factors ranging from 0.51 to 0.67, at a power output of 22 to 56 W. One 38–50 W PSC motor was evaluated and it was found that its peak efficiency was 50% with a power factor of 0.98 at a power output of 40 W. Finally, one 38–50 W shaded pole motor was evaluated and it was found that its peak efficiency was 27% with a power factor of 0.64 at a power output of 47 W.

7.2.2 Airflow Testing of Fan Motor Technologies

Airflow testing of shaded-pole, PSC, EC, and PMS motor/fan assemblies was performed using an airflow test chamber, which was designed in accordance with ANSI/AMCA Standard 210-16/ASHRAE Standard 51-16, to measure the performance of the subject motor/fan assembly and to determine the incumbent display case system impedance (AMCA 2016). The airflow test setup, procedure and results were discussed.

In an effort to match the airflow rate between the incumbent motor/fan assembly, operating at a nominal 1550 RPM, and the retrofit PMS motor/fan assembly, operating at a synchronous 1800 RPM, an appropriately pitched fan blade must be installed in the PMS motor/fan assembly. To that end, a family of fan curves (static pressure vs airflow rate and electrical power input vs airflow rate) was generated for the 6–12 W PMS motor/fan assemblies with 8-inch fan blades pitched from 17 to 32 degrees. A similar set of curves was generated for the 38–50 W motors paired with 10 and 12-inch blades. Various incumbent motor/fan assemblies were also tested in the laboratory airflow test chamber and their fan curves were generated.

To determine the incumbent display case system impedance (static pressure) and the incumbent motor/fan assembly operating point, measurements of the electrical power supplied to the incumbent motor/fan assembly were taken in the field. The operating point and airflow rate of the incumbent motor/fan assembly in the incumbent display case were then determined by locating the measured electrical power on the plot of electrical power input versus airflow rate from the airflow test done in the laboratory. An appropriately pitched fan blade was then installed in the PMS motor/fan assembly to replicate the airflow rate and static pressure of the incumbent motor/fan assembly in the vicinity of its operating point. This operating point represents the impedance of the incumbent display case.

7.2.3 PMS and Incumbent Motor/Fan Assembly Airflow Performance Comparison

It is not practical or cost effective to perform laboratory airflow testing on every motor/fan assembly replaced in a whole-store retrofit. Therefore, a wide variety of incumbent motor/fan assemblies were tested in the laboratory to determine their airflow performance. Based on the results of these tests, the PMS motor manufacturer standardized its motor/fan blade pitch configuration as follows:

- 6–12 W PMS motor, 8-inch fan blade pitch: 25°
- 38–50 W PMS motor, 10-inch fan blade pitch: 22°
- 38–50 W PMS motor, 12-inch fan blade pitch: 18°

To validate these standard pitched blades, several incumbent motors that were replaced in a whole-store retrofit were returned to the laboratory for comparison airflow testing. It was found that the standardized PMS motor/fan assemblies delivered the same or greater airflow rate with reduced power consumption over the full range of airflow rates.

7.3 FIELD EVALUATIONS OF FAN MOTOR TECHNOLOGIES

7.3.1 Display Case Evaporator Fan Motors

Field evaluation of refrigerated display case evaporator fan motors was accomplished by performing side-by-side comparisons of 6–12 W PMS motors to 6–12 W shaded-pole and EC evaporator fan motors. A total of six test sites were used for the side-by-side field evaluation of the various evaporator fan motor technologies. At each test site, either one display case was used, in which an equal number of incumbent and PMS evaporator fan motors were installed (with one motor type in each half of the display case) or two identical display cases were used, in which one display case contained the incumbent fan motors while the other case contained an equal number of PMS fan motors.

It was found that, on average, a PMS motor consumes 79% less power and draws 82% less current than a shaded pole motor, and on average, 34% less power and 49% less current than an EC motor. In addition, the PMS motor exhibits an average power factor of approximately 0.82, which is on average 40% greater than that of existing evaporator fan motors. It was found that the effect of evaporator fan motor type on the discharge and return air temperatures is negligible.

7.3.2 Walk-In Cooler/Freezer Evaporator Fan Motors

Two field test sites were selected to evaluate the performance of the larger 38 to 50 W PMS evaporator fan motors in walk-in cooler/freezer applications. At each supermarket, two walk-in units were selected for investigation: one walk-in dairy cooler and one walk-in freezer.

The data collected from one of the test sites indicates that a significant energy savings is possible when retrofitting incumbent walk-in cooler and freezer evaporator fan motors to PMS motors. A 61% decrease in fan motor power was measured when retrofitting existing evaporator fan motors with PMS motors in the walk-in cooler. In addition, a 48% decrease in fan motor power was measured when retrofitting existing evaporator fan motors with PMS motors in the walk-in freezer. Unfortunately, the data collected from the other test site resulted in inconclusive results due to anomalies in the measured data.

7.3.3 Whole Store Evaporator Fan Motor Retrofits

The culmination of the field evaluation of fan motor technologies was a whole-store retrofit conducted at a supermarket. Pre- and post-retrofit measurement of evaporator fan motor power in medium- and low-temperature refrigerated display cases and walk-in coolers/freezers was performed. A total of 22 display case line-ups on 22 separate electrical circuits, and 16 walk-in coolers/freezers, on 20 separate electrical circuits were monitored during the whole-store evaporator fan motor retrofit. In this whole-store retrofit, 103 EC motors and 82 shaded pole motors were replaced in the refrigerated display cases, and 73 PSC motors and 4 EC motors were replaced in the walk-ins. Overall for the whole-store retrofit, the current supplied to all monitored evaporator fan motors was reduced by 52%, the real power was reduced by 46% and the apparent power was reduced by 51% following the retrofit of the 262 evaporator fan motors that were monitored.

Based on the total installed cost of the replaced and monitored evaporator fan motors and the estimated annual energy cost savings, the simple payback period was calculated to be 5.6 years. Utility incentives may be applicable and could be applied to reduce the simple payback period. In addition, installation of more efficient evaporator fan motors will reduce the heat load imposed on the display cases and the walk-in coolers/freezers, resulting in compressor energy savings. Factoring in both utility incentives and the reduction in compressor energy consumption would further reduce the simple payback period.

7.4 POTENTIAL SITE AND SOURCE ENERGY SAVINGS

Based on the results of the laboratory and field evaluations of evaporator fan motors, the potential site and source energy savings associated with retrofitting the existing installed base of 6–12 W and 38–50 W commercial refrigeration evaporator fan motors with PMS fan motors was estimated.

From a survey of the installed base, it was estimated that there are approximately 15.8×10^6 6–12 W and 14.4×10^6 38–50 W evaporator fan motors installed in commercial refrigeration equipment and beverage vending machines. It was estimated that 15.1×10^9 kWh per year of site electricity is consumed by the existing installed base of 6–12 W and 38–50 W evaporator fan motors, with associated CO_2 emissions of 25.2×10^9 lb. If all currently installed 6–12 W and 38–50 W evaporator fan motors were retrofitted with PMS fan motors, the total site electricity consumption was estimated to be 8.0×10^9 kWh per year, with associated CO_2 emissions of 13.4×10^9 lb. Thus, the total retrofit of all evaporator fan motors represents a site energy savings of approximately 7.1×10^9 kWh/year (47% reduction), and an annual CO_2 emissions reduction of 11.8×10^9 lb (47% reduction), compared with the baseline. The annual source energy savings associated with the PMS evaporator fan motor retrofit was estimated to be 0.076 quad/year.

7.5 EFFECTS OF FAN MOTOR POWER FACTOR

From the dynamometer test results, the power factor of the PMS motor is approximately 30% better than that of shaded-pole, PSC and EC motors. For the same real power output, a load with a low power factor requires more current than a load with a high power factor. Thus, PMS fan motors, with their high power factor, will consume less current than motors with a lower power factor. The lower current draw of the PMS motors means reduced generation and transmission costs for the utility company. Comparing the baseline case of shaded-pole, PSC and EC motors with an installed base of PMS motors, it was found that utilities would be required to supply 54% less apparent power and 54% less current for PMS motors compared with the baseline combination of shaded-pole, PSC and EC motors.

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APPENDIX A. ADDITIONAL WALK-IN COOLER/FREEZER EVAPORATOR FAN MOTOR PERFORMANCE DATA

APPENDIX A. ADDITIONAL WALK-IN COOLER/FREEZER EVAPORATOR FAN MOTOR PERFORMANCE DATA

Walk-In Cooler – South Burlington, VT Supermarket

Additional evaporator fan motor performance data is provided in Appendix A for the left, right and far-right evaporator coils in the walk-in dairy cooler at the South Burlington, VT supermarket, as a supplement to the data presented in Section 4.2.2.1.

Fig. 40 shows the evaporator fan motor power, current and power factor for the left evaporator in the walk-in dairy cooler at the South Burlington, VT, store for the period 20 April 2017 through 6 July 2017. The incumbent evaporator fan motors were replaced with PMS motors on 16 June 2017.

As shown in Fig. 40, the average combined power of the three incumbent fan motors in the left evaporator was found to be 376 W during the period 3 May through 16 June. The average combined power of the three PMS fan motors in the left evaporator was 153 W during the post-retrofit period 16 June 2017 to 6 July 2017. Post retrofit, the PMS motors were found to use 59% less power than the incumbent motors.

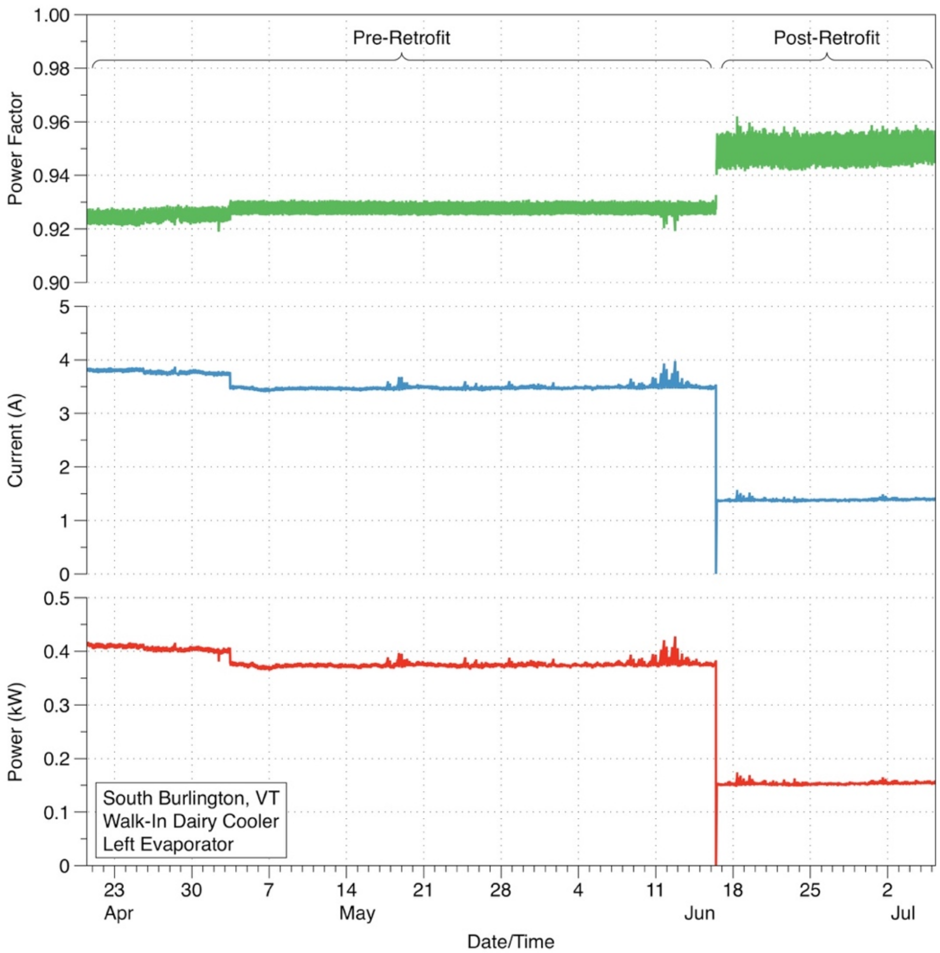

Fig. 40. Pre- and post-retrofit evaporator fan power, current and power factor for the left evaporator in the walk-in dairy cooler, South Burlington, VT.

Fig. 41 shows the evaporator fan motor power, current and power factor for the right evaporator in the walk-in dairy cooler at the South Burlington, VT, store for the period 20 April 2017 through 6 July 2017. The incumbent evaporator fan motors were replaced with PMS motors on 16 June 2017.

As shown in Fig. 41, the average combined power of the three incumbent fan motors in the right evaporator was found to be 342 W during the period 3 May through 16 June. The average combined power of the three PMS fan motors in the right evaporator was 136 W during the post-retrofit period 16 June 2017 to 6 July 2017. Post retrofit, the PMS motors were found to use 60% less power than the incumbent motors.

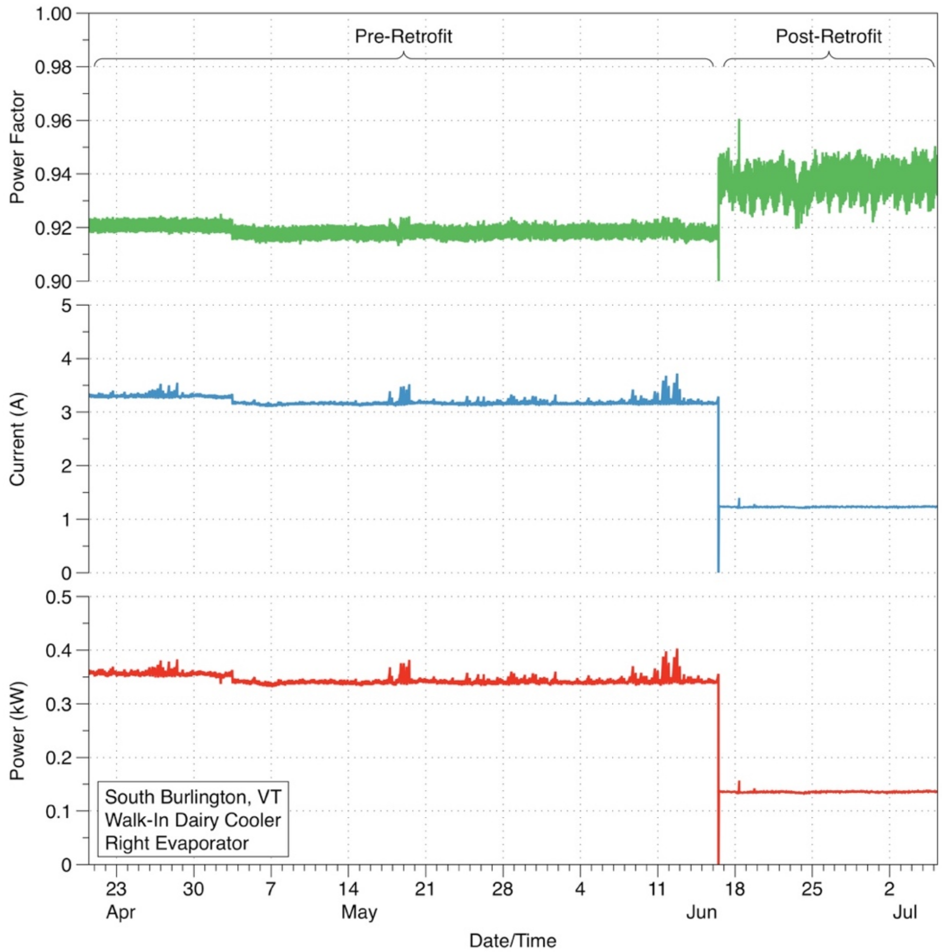

Fig. 41. Pre- and post-retrofit evaporator fan power, current and power factor for the right evaporator in the walk-in dairy cooler, South Burlington, VT.

Fig. 42 shows the evaporator fan motor power for the far-right evaporator in the walk-in dairy cooler at the South Burlington, VT, store for the period 20 April 2017 through 6 July 2017. The incumbent evaporator fan motors were replaced with PMS motors on 16 June 2017.

As shown in Fig. 42, the average combined power of the three incumbent fan motors in the far-right evaporator was found to be 333 W during the period 3 May through 16 June. The average combined power of the three PMS fan motors in the far-right evaporator was 123 W during the post-retrofit period 16 June 2017 to 6 July 2017. Post retrofit, the PMS motors were found to use 63% less power than the incumbent motors.

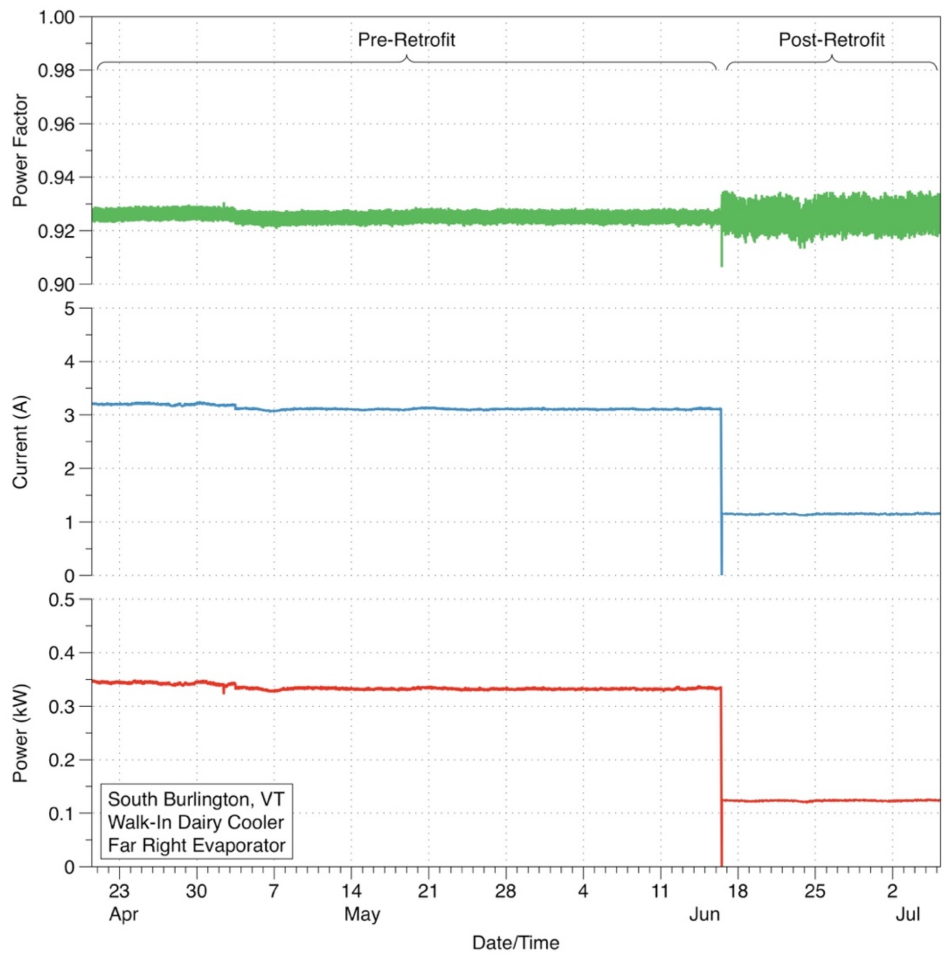

Fig. 42. Pre- and post-retrofit evaporator fan power, current and power factor for the far-right evaporator in the walk-in dairy cooler, South Burlington, VT.

Walk-In Freezer – South Burlington, VT Supermarket

Additional evaporator fan motor performance data is provided in Appendix A for the middle evaporator in the walk-in freezer at the South Burlington, VT supermarket, as a supplement to the data presented in Section 4.2.2.2.

Fig. 43 shows the evaporator fan motor power for the middle evaporator in the walk-in freezer at the South Burlington, VT, store for the period 20 April 2017 through 3 August 2017. The incumbent evaporator fan motors were replaced with PMS motors on 16 June 2017. It can be seen that evaporator fan motor power is relatively constant prior to and following the motor retrofit, and a significant drop in fan power is noted following the installation of the PMS evaporator fan motors.

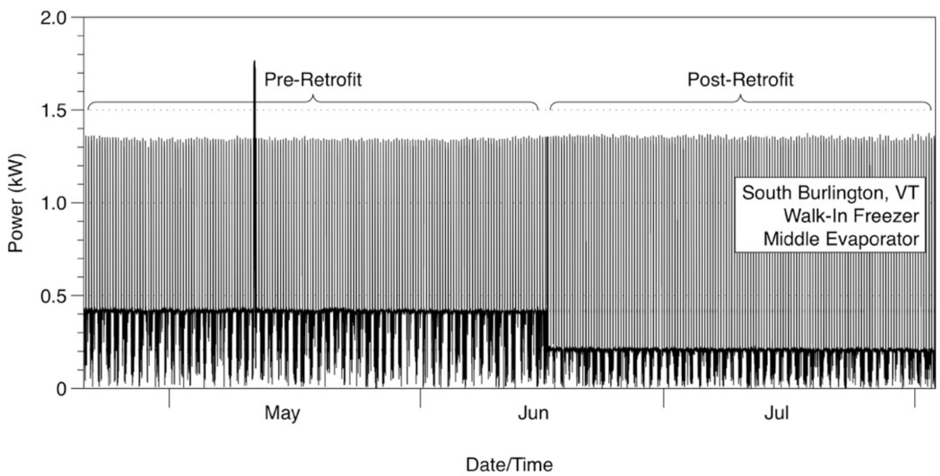

Fig. 43. Pre- and post-retrofit evaporator fan power for the middle evaporator in the walk-in freezer, South Burlington, VT.

Fig. 44 shows the total power, current and power factor of the four incumbent fan motors in the middle walk-in freezer evaporator for a typical day during the pre-retrofit measurement period. Power fluctuates from zero when the freezer door is open or when cooling is not required, to an average value of 416 W when the four evaporator fans are operating. The peak power of approximately 1.35 kW occurs three times per day during the defrost cycle, each of which lasts approximately 35 minutes.

Similarly, Fig. 45 shows the total power, current and power factor of the four PMS fan motors in the middle walk-in freezer evaporator for a typical day during the post-retrofit measurement period. Power fluctuates from zero when the freezer door is open or when cooling is not required, to an average value of 207 W when the four evaporator fans are operating.

Assuming that the total power of the four incumbent evaporator fan motors for the middle evaporator is on average 416 W, and similarly that the total power of the four PMS evaporator fan motors is on average 207 W, the PMS motors are shown to use 50% less power than the incumbent motors.

As noted previously, it was intended that the evaporator coils would be cleaned prior to the fan motor performance evaluation. Since no significant decrease in fan motor power was noted during the pre-retrofit data collection, it would appear that the middle freezer coil at the South Burlington, VT, store was not cleaned.

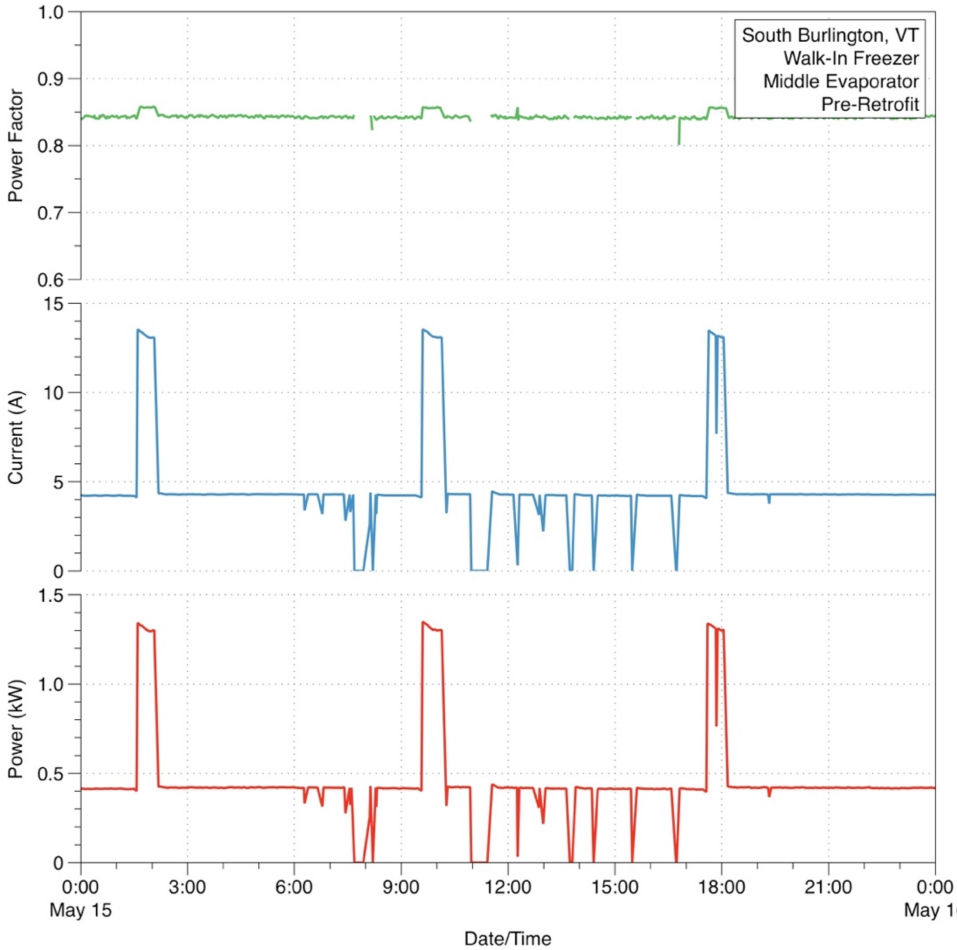

Fig. 44. Pre-retrofit evaporator fan power, current and power factor for the middle evaporator in the walk-in freezer, South Burlington, VT, for 15 May 2017 (typical).

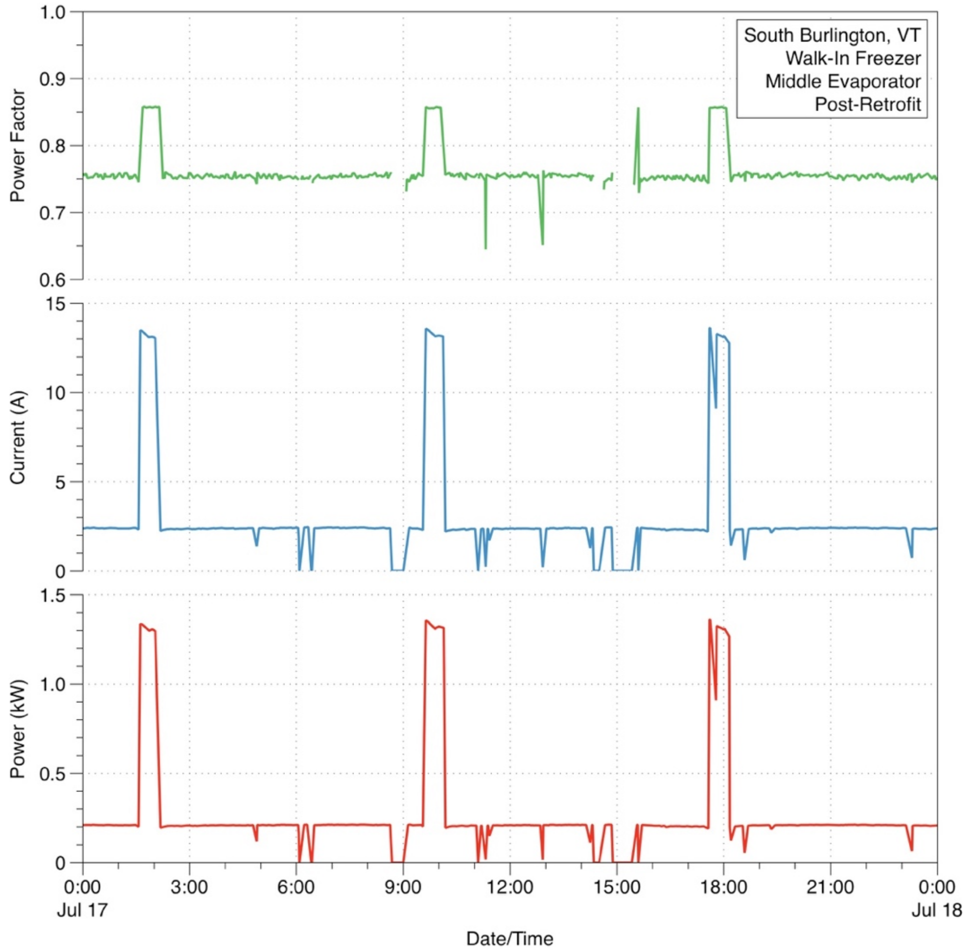

Fig. 45. Post-retrofit evaporator fan power, current and power factor for the middle evaporator in the walk-in freezer, South Burlington, VT, for 17 July 2017 (typical).