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Condensing Furnace Venting Part 2: Evaluation of Same-Chimney Vent Systems for Condensing Furnaces and Natural Draft Water Heaters

Ayyoub M. Momen
Jeffrey Munk
Patrick Hughes

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Energy and Transportation Science Division

CONDENSING FURNACE VENTING PART 2: EVALUATION OF SAME-CHIMNEY VENT SYSTEMS FOR CONDENSING FURNACES AND NATURAL DRAFT WATER HEATERS

Ayyoub M. Momen
Jeffrey Munk
Patrick Hughes

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CONTENTS

Page

LIST OF FIGURES V
LIST OF TABLES VII
ACKNOWLEDGMENTS IX
ABBREVIATIONS AND DEFINITIONS XI
EXECUTIVE SUMMARY XIII
1. INTRODUCTION 1
2. UPDATED VENTING SOLUTIONS EVALUATED 3
2.1 INDUSTRY VENTING SOLUTIONS EVALUATED 3
2.1.1 M&G DuraVent Solutions 3
2.1.2 Minor Adaptations of Commercially Available Fan-Assisted Products 5
2.2 ENTRAINVENT DEVELOPED AT ORNL 6
3. EVALUATION METHODOLOGY 9
3.1 METRICS THAT CAPTURE VENT PERFORMANCE 9
3.2 PERFORMANCE METRIC MEASUREMENT APPROACH 11
3.3 VENT PERFORMANCE EVALUATION APPROACH 12
4. EVALUATION RESULTS 19
5. CONCLUSIONS 23
6. REFERENCES 25
APPENDIX A: THEORETICAL BACKGROUND A-1
APPENDIX B: DATA SUPPORTING THE EVALUATION RESULTS B-1
APPENDIX C: APPLIANCE, CHIMNEY, VENT CONNECTOR, AND SOLUTION SPECIFICATIONS C-1

LIST OF FIGURES

Figure **Page**

Fig. 1. M&G DuraVent B vent reline solution installed inside the original Type B metal chimney. 3
Fig. 2. M&G DuraVent reline solutions installed inside the original masonry chimney: (a) dual-flex reline option; (b) single-flex reline option. 4
Fig. 3. Fan-assisted water heater dual-reline solution installed inside the original masonry chimney. 6
Fig. 4. Illustration of secondary flow caused by jet entrainment. 7
Fig. 5. EntrainVent single-reline solution installed inside the original masonry chimney. 8
Fig. 6. Schematic representation of the thermocouples used for CVEP and WVMD testing in the "dilution air temperature" approach. 10
Fig. 7. Data illustrating the dilution air temperature method for determining the value of CVEP. 11
Fig. 8. Data illustrating the dilution air temperature method for determining the value of WVMD. 12
Fig. 9. CVEP and WVMD for baseline water heater–only operation on the masonry chimney. 14
Fig. 10. CVEP and WVMD for M&G DuraVent single-flex reline solution [see Fig. 2(b)] water heater–only operation on the masonry chimney. 15
Fig. 11. Relationship between average chimney temperature and outdoor air temperature during baseline water heater–only CVEP tests on the masonry chimney. 16
Fig. 12. Determination of CVEP and WVMD from baseline and M&G DuraVent single-flex reline solution [see Fig. 2(b)] water heater–only test data for the masonry chimney. 17
Fig. 13. Measurement and theory-derived values of volumetric flow of flue gases up the baseline masonry chimney during water heater–only operation. 18

LIST OF TABLES

Table **Page**

Table 1. BPI combustion appliance zone depressurization limits for natural draft appliances (BPI 2012) 13
Table 2. CVEP and WVMD performance comparison: Masonry chimney baseline versus the M&G DuraVent single-flex reline solution [see Fig. 2(b)] installed inside the original masonry chimney 18
Table 3. CVEP and WVMD performance comparison: Type B metal chimney baseline versus the M&G DuraVent B Vent reline solution (see Fig. 1) installed inside the original Type B metal chimney 19
Table 4. CVEP and WVMD performance comparison: masonry chimney baseline versus the M&G DuraVent dual-flex reline solution [see Fig. 2(a)] installed inside the original masonry chimney 20
Table 5. CVEP and WVMD performance comparison: masonry chimney baseline versus the M&G DuraVent single-flex reline solution [see Fig. 2(b)] installed inside the original masonry chimney 20
Table 6. CVEP and WVMD performance comparison: masonry chimney baseline versus the fan-assisted water heater dual-reline solution (see Fig. 3) installed inside the original masonry chimney 21
Table 7. CVEP and WVMD performance comparison: masonry chimney baseline versus the EntrainVent single-reline [chimney serviceable] solution (see Fig. 5) installed inside the original masonry chimney 21
Table 8. CVEP for water heater–only operation for all baseline and solution venting system configurations experimentally evaluated in this study 23

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ABBREVIATIONS AND DEFINITIONS

ΔP	test room (chamber) pressure minus outdoor pressure
ΔT	spatially averaged chimney temperature (bottom-to-top) minus outdoor temperature
AFUE	annual fuel utilization efficiency
Backdrafting	flue gases from a fan-assisted furnace backflowing through the water heater vent connector and out of the water heater draft hood into the building rather than rising out of the chimney into the atmosphere
Baseline	existing vent configuration for a common-vented noncondensing furnace and natural draft water heater
BPI	Building Performance Institute
Category I	gas appliances, such as noncondensing furnaces, based on natural draft combustion served by negative static pressure vents designed so that vent gas temperature remains high enough to avoid excessive condensation in the vent
Category IV	gas appliances, such as condensing furnaces, based on forced draft combustion served by positive static pressure vents
CFM	cubic feet per minute
Chimney	a structure or vent of any material (including masonry and metal) used to exhaust combustion products vertically into the atmosphere
CVEP	cold vent establishment pressure
DOE	US Department of Energy
Downdrafting	flow of outdoor air down a chimney into the building
Furnace	for purposes of this report, a device that provides space heating through an air distribution system, is fueled by natural gas or propane, with a heat input rating of <225,000 Btu/h, but excluding special classes also covered by existing standards such as mobile home furnaces or small furnaces (<45,000 Btu/h)
OAT	outdoor air temperature
ORNL	Oak Ridge National Laboratory
Spilling	flue gases from a draft hood–equipped appliance spilling into the building rather than being captured by the draft hood and rising out of the chimney into the atmosphere
$T_{chimney}$	spatially averaged chimney temperature (bottom to top)
T_{out}	outside air temperature
Type B	metal vent of double-wall construction with the inner wall typically being aluminum and the outer being galvanized steel. Commonly used with Category I appliances
WVMD	warm vent maximum depressurization

EXECUTIVE SUMMARY

In 1987, the National Appliance Energy Conservation Act prescribed the first federal minimum energy conservation standard for natural gas furnaces at an annual fuel utilization efficiency of 78%, effective January 1, 1992. One of the techno-economic issues that has prevented higher furnace efficiency standards since then is the lack of cost-effective, simple, and safe solutions that enable condensing furnaces and atmospheric combustion water heaters to vent through the same existing chimney.

Part 1 of this two-part report series, published in October 2014, documents the issue, prospective solutions, and a test laboratory established to evaluate prospective venting solutions. This part 2 report documents the updated prospective solutions (because they have evolved since part 1 was written), the methodology for experimentally evaluating prospective solutions, and results of the evaluations.

The fundamental issue is that higher furnace efficiency standards would require the use of condensing furnaces; and when existing noncondensing furnaces are replaced and the costs of modifying the venting systems considered, it is unclear whether this requirement is cost effective in all applications. It might be possible to reuse existing vertical vents as chases for new condensing furnace venting systems. If not, where physical constraints and codes allow, it might be possible to install new horizontal side-wall vent systems. Where these options are not feasible, running new vertical vents through buildings and roofs would be an alternative, albeit at additional cost.

The most challenging application is when the existing noncondensing furnace and a draft hood–equipped atmospheric combustion water heater are commonly vented up the same chimney and a side-wall vent for the new condensing furnace is not an option. Cost-effective, commercially available solutions that enable condensing furnaces and atmospheric combustion water heaters to vent through the existing vertical chimney are needed.

In this study, a search for solutions was undertaken that included efforts devoted to inventing new solutions and monitoring developments by industry. Several prospective solutions were identified that appear to be simple and cost effective for retrofitting into Type B metal chimneys and/or masonry chimneys. Solutions for both metal and masonry chimneys are emerging from M&G DuraVent, the North American arm of M&G Group, believed to be the largest vent products company in the world. Another prospective solution is a minor adaptation of commercially available fan-assist kits for retrofitting draft hood–equipped water heaters. An additional prospective solution is known as EntrainVent, a precommercial invention by Oak Ridge National Laboratory. Although these prospective solutions were described in detail in the part 1 report, they have evolved since, and updated descriptions are provided in this report.

A new furnace and water heater venting system test laboratory (described in detail in the part 1 report) was established to implement an experimental program of evaluation for the prospective solutions. The experimental methodology for evaluating prospective solutions is described in detail in this report.

This project provided the first full-scale chimney evaluations of the prospective solutions in an experimental facility capable of independently controlling indoor depressurization. Five prospective solutions (one for Type B metal chimneys and four for masonry chimneys) were evaluated experimentally. Summary tables were generated for each solution, with results included for two configurations (baseline and solution), three operating cases per configuration (water heater only, furnace and water heater, and furnace only), and two performance metrics, for a total of 12 performance values per solution. Hence there were 60 measures of performance across all five solutions.

For the most challenging case—water heater–only operation—all of the solutions evaluated had the capability to establish a draft through a cold vent at a lower indoor depressurization level than the baseline chimney configurations. In other words, they performed better than the baseline chimneys, which suggests that all of the solutions evaluated in this study would provide adequate vent performance. At the same time, all of these solutions enable condensing furnaces and atmospheric combustion water heaters to vent through the same chimney, eliminating the need for expensive renovations in challenging condensing furnace installations.

1. INTRODUCTION

One of the techno-economic issues that has prevented higher furnace efficiency standards is the lack of cost-effective, simple, and safe solutions that enable condensing furnaces and atmospheric combustion water heaters to vent through the same existing chimney.

Part 1 of this two-part report series was published in October 2014 and documents the issues, prospective solutions, and venting system test laboratory established to evaluate prospective solutions (Momen et al. 2014). This part 2 report documents the updated prospective solutions, the methodology for evaluating prospective solutions, and the results of the evaluations.

Section 2 provides updated detailed descriptions of the prospective venting system solutions enabling condensing furnaces and atmospheric combustion water heaters to vent through the same vertical chimney. Section 3 provides a detailed description of the experimental methodology used to evaluate the prospective solutions. Section 4 presents the evaluation results. Section 5 provides a discussion of the summary conclusions. Appendix A provides theoretical background, Appendix B presents the data supporting the evaluation results, and Appendix C documents the specifications for the solutions evaluated and the appliances, chimneys, and vent connectors used to do so.

2. UPDATED VENTING SOLUTIONS EVALUATED

2.1 INDUSTRY VENTING SOLUTIONS EVALUATED

2.1.1 M&G DuraVent Solutions

Solutions for both metal and masonry chimneys are emerging from M&G DuraVent, the North American arm of M&G Group, believed to be the largest vent products company in the world. In general, these vent upgrade systems enable reuse of existing metal or masonry chimneys and consist of a new vent cap and appropriate liner(s).

If the existing chimney is Type B double-wall metal, as depicted in Fig. 1, the retrofit involves replacing the existing vent cap with a new one that supports a flexible stainless steel liner inserted down the metal chimney to serve as the flue for the new condensing furnace. The annular space between the liner and the original Type B inner chimney wall serves as the flue for the water heater. The two flue streams remain separated and are exhausted individually to the atmosphere.

Fig. 1. M&G DuraVent B vent reline solution installed inside the original Type B metal chimney.

If the existing chimney is masonry, as depicted in Fig. 2, the retrofit involves replacing the existing vent cap with a new one that supports either one or two flexible liners, depending on a number of factors [climate, exterior (exposed to outdoors) or interior chimney location, code-compliant vent size for the

equipment vented, and whether the chimney has a liner (e.g., clay tile) and the liner remains in good condition]. It is anticipated that in most cases two liners will be required [Fig. 2(a)], where the left-hand liner is flexible aluminum and serves as the flue for the water heater and the right-hand liner is flexible stainless steel and serves as the flue for the new condensing furnace. Since condensation is expected in the condensing furnace vent, it is made of corrosion-resistant stainless steel. The natural-draft water heater has much hotter vent temperatures and enough dilution air that minimal condensation is expected, allowing the use of less expensive aluminum. The two flue streams remain separated and are exhausted individually to the atmosphere. In cases where the masonry chimney has a liner in good condition, which meets the size requirements in the National Fuel Gas Code (NFPA 2012) after the area occupied by the condensing furnace liner is deducted, and excessive condensation is not an issue (mild climate or interior chimney location), then a single liner may suffice [Fig. 2(b)] where the clay-tile liner serves as the flue for the water heater and the flexible aluminum liner is not needed. Although this configuration would be lower cost and appears technically viable, it should be noted that, as currently written, Sect. 12.6.8.1 of NFPA 54 excludes its use.

(a) **(b)**

Fig. 2. M&G DuraVent reline solutions installed inside the original masonry chimney: (a) dual-flex reline option; (b) single-flex reline option.

2.1.2 Minor Adaptations of Commercially Available Fan-Assisted Products

Category I noncondensing, fan-assisted furnaces supplanted draft hood–equipped furnaces many years ago, enabling reduced off-cycle losses and annual fuel utilization efficiency (AFUE) ratings of noncondensing furnaces in the neighborhood of 80%. The vent pressure in a fan-assisted furnace is still negative (hence the Category I designation) because the draft action in a properly sized Category I vent will be stronger than the fan pressure rise. In addition, the vent gas temperature of these appliances is in the same range as traditional, draft hood appliances since the higher flue exit temperatures of draft hood appliances are moderated with greater amounts of dilution air.

Fan-assist kits for retrofitting draft hood–equipped water heaters are also commercially available (e.g., http://www.tjernlund.com/Tjernlund_CSA1_Chimney_Stack_Assist_Fan_Kit_8500605.pdf). These products are designed to ensure that orphaned water heaters (when a noncondensing furnace is removed from a common vent leaving only a natural draft water heater, it is considered orphaned) will vent properly in a preexisting chimney after the old Category I furnace is removed and the new Category IV condensing furnace is separately side-wall vented. The kits come with safety interlocks that essentially prevent fuel flow to the water heater unless the fan is operating. Relatively minor modifications to existing fan-assist kits could also provide a solution to the orphaned water heater problem in applications where the old Category I furnace is removed and the new Category IV condensing furnace must be vented through the existing vertical chimney because venting through a side wall is not possible.

One option along these lines was built and evaluated. For the case of a preexisting clay tile–lined masonry chimney, a fan-assist was installed on the vent connector between the water heater and chimney inlet. The version built has a stronger fan-assist than the typical water heater kit, akin to those built into condensing furnaces or into packaged units with gas heating, so that dilution air would be sufficient to keep flue temperatures low enough to enable use of lower cost chimney liner materials for the water heater. This fan would cause positive pressure in the vent downstream of the fan and would therefore need a sealed vent similar to Category III or IV appliances depending on the quantity of dilution air mixed with the flue gas. A separate liner was installed in the masonry chimney for the condensing furnace. In this configuration, the large quantity of dilution air ensures a low concentration of water vapor in the water heater liner, minimizes condensation, and moderates flue gas temperature. A rendering of the fan-assisted water heater option is shown in Fig. 3. Schematically, this configuration is identical to Fig. 2(a); however, it is believed that lower cost chimney liner materials could be used because of the reduced risk of condensation and lower flue gas temperatures.

Fig. 3. Fan-assisted water heater dual-reline solution installed inside the original masonry chimney.

2.2 ENTRAINVENT DEVELOPED AT ORNL

Invention disclosure #201303220 filed December 10, 2013, describes EntrainVent, which leverages the same physical phenomenon that has been widely and successfully applied in ejector, vacuum jet, and carburetor technologies.

Theoretically, when a jet discharges to a larger space, the flow shear stress causes entrainment of the ambient flow into the jet stream. Consider the case of concentric pipes of diameter D1 and D2, as shown in Fig. 4. The flow in the inner pipe having diameter D1 is the powered exhaust of gaseous combustion products from the condensing furnace. The inner pipe flow acts as a jet, and the resulting entrainment causes a negative pressure, which induces a secondary flow in the annular space between the inner and outer pipes serving as the vent for the natural draft water heater.

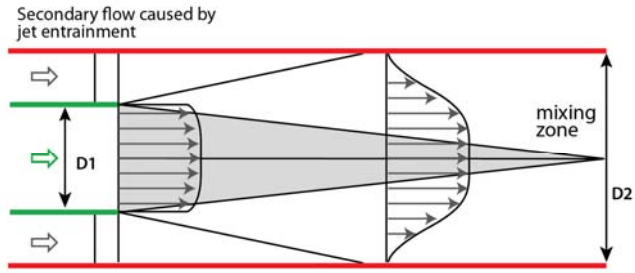

Fig. 4. Illustration of secondary flow caused by jet entrainment.

EntrainVent is integrated into the vent cap at the top of the chimney, where it produces a negative pressure on the water heater vent, causing flue gases to rise and discharge from the top of the chimney under any ambient temperature and wind conditions. The vent cap is completely passive, and no sensors, controls, or dampers with actuators are required. EntrainVent exploits the kinetic energy of the condensing furnace flue gas, which would otherwise be dissipated to the atmosphere. Depending on the geometry, this solution could increase the load on the condensing furnace power vent. Testing could be done to determine the equivalent length of straight pipe that would result in the same pressure drop for incorporation into venting tables, similarly to how elbows are handled.

With EntrainVent, establishing the draft for the water heater vent is no longer a problem whenever the condensing furnace is operating. At other times, a controls interconnect between the water heater and condensing furnace is required that essentially prevents fuel flow to the water heater until the condensing furnace power vent is operating.

Several possible EntrainVent configurations are documented, but only the one illustrated in Fig. 5 is evaluated here. The retrofit involves replacing the existing vent cap with a new one that integrates EntrainVent and supports a single liner to serve as the flue for the new condensing furnace. The annular space between the new liner and the clay tile-lined masonry chimney serves as the flue for the water heater. The two flue streams mix at the vent cap and are exhausted to the atmosphere.

Schematically, the EntrainVent configuration evaluated (Fig. 5) resembles the M&G DuraVent single-flex reline solution [Fig. 2(b)]. For this configuration, the masonry chimney must have a liner in good condition. However, EntrainVent is an active venting solution much like the fan-assisted water heater vent described in Sect. 2.1.2, so the size requirements (as currently written) in the National Fuel Gas Code (NFPA 2012) after the area occupied by the condensing furnace liner is deducted do not apply. Further, with this active vent concept, the dilution air entering the water heater vent (which surrounds the condensing furnace liner) moderates the liner exposure temperature (potentially enabling the use of lower cost liner materials) and reduces condensation potential on the clay-tile liner. Although this configuration appears technically viable it should be noted that, as currently written, Sect. 12.6.8.1 of NFPA 54 excludes its use.

One of the other EntrainVent configurations resembles the M&G DuraVent dual-flex reline solution [Fig. 2(a)], but it was not evaluated in this study. Implementing any of the EntrainVent concepts would require a controls interconnect preventing fuel flow to the water heater until the condensing furnace power vent is operating.

Fig. 5. EntrainVent single-reline solution installed inside the original masonry chimney.

3. EVALUATION METHODOLOGY

Part 1 of this two-part report series was published in October 2014 and documents, among other things, the venting system test laboratory established to evaluate prospective solutions. Familiarity with this section of the previous report will enhance comprehension of the evaluation methodology described subsequently.

3.1 METRICS THAT CAPTURE VENT PERFORMANCE

Natural draft vent performance in a real building is affected by many factors, including the chimney height and cross section, heat input from the vented appliances, vent connections between the appliances and chimney, vent material, wind, temperature, and building depressurization. Establishing the facilities necessary to independently control all of these variables as part of an experimental evaluation was well beyond the resources and calendar time made available for this project. Instead, the chimney height, appliances, and vent connections between the appliances and chimney were held constant between the baseline and proposed solutions, and the vent performance under various levels of building depressurization and outdoor air temperature was measured.

Each solution was evaluated against a baseline configuration of a noncondensing furnace commonly vented with a natural draft water heater, which was meant to represent existing equipment before upgrading the furnace to a condensing model. The existing building stock includes diverse configurations of commonly vented furnaces and water heaters. For the purposes of this evaluation, a specific noncondensing furnace and water heater commonly vented through a specific Type B metal chimney served as one baseline, and the same equipment commonly vented through a specific clay tile–lined masonry chimney located indoors served as a second baseline. Vent performance of each baseline was determined experimentally. Then the furnace was upgraded to the condensing model, a prospective vent solution was installed, and vent performance was evaluated experimentally. This process was repeated for all solutions identified for each chimney type. While testing the baselines and solutions, care was taken so that the vent connectors between the appliances and chimneys were identical to the extent possible. This was done to preserve the fidelity of the baseline versus solution comparisons, which is the primary basis of the evaluation.

Input from the weatherization community indicates that old masonry chimneys are often oversized but nonetheless are used for venting modern natural draft appliances, while Type B metal chimneys tend to be newer and are more likely to be properly sized. Based on this information the clay tile–lined masonry chimney established in the laboratory is larger than the NFPA 54 sizing standard requirement given the heat inputs of the selected noncondensing furnace and water heater. However, this masonry chimney has adequate vent performance in baseline mode and with the condensing furnace and various vent solutions installed in the chimney, which provides the baseline versus solution data needed for the experimental evaluation. If the vent performance of a solution meets or exceeds the baseline in an oversized masonry chimney, the solution's draft performance would only improve on a code-compliant chimney. Of course the expectation for any commercialized venting solution is that both the condensing furnace and the natural-draft water heater will have a code-compliant vent after the solution is installed, regardless of whether or not the preretrofit vent system was code compliant.

Two common metrics were chosen for evaluating venting performance. The first metric—the cold vent establishment pressure (CVEP)—equals the lowest indoor negative pressure (depressurization level) at which the appliance still has the ability to establish an upward natural draft through a downdrafting cold vent. This is an extremely challenging condition because on appliance startup the flue gases from the appliance must overcome an established cold flow down the vent caused by depressurization. In this test the appliance is fired with the chamber at a very high level of depressurization that is known to cause

spilling. The depressurization of the chamber is then gradually decreased until spilling ceases. The second metric—the warm vent maximum depressurization (WVMD)—equals the depressurization level at which an operating appliance on a warm vent still has the ability to maintain a draft. In this test the appliance is fired with the chamber under neutral or positive pressure. The chamber is then gradually depressurized until the appliance begins spilling. The CVEP test is taken directly from the American Society for Testing and Materials ASTM E1998-11 test procedure (ASTM International 2011). The WVMD test is a maximum depressurization test that would be done in a home or adapted to a test chamber environment and is similar to the hot vent reversal pressure test used by Timusk et. al. (1988).

Both the CVEP and the WVMD tests require some means of determining when spillage or backdrafting is occurring. The "dilution air temperature" approach involves measuring the temperature of the air surrounding the draft hood of the water heater. This is shown schematically in Fig. 6, but in reality four thermocouples that were shielded from radiant heat with aluminum foil tape and equally spaced around the circumference of the draft hood were used to measure this temperature. Under normal draft conditions, the temperature of this air will be similar to that of the chamber. When the water heater is spilling or flue gas from the operating furnace is backdrafting through the water heater draft hood, this temperature will be much higher than the chamber temperature. The "chimney pressure" approach involves measuring the pressure differential between the chimney and the test chamber. When the chimney pressure is negative relative to the chamber, air flows from the chamber into the chimney. This does not guarantee that all flue gases are being captured by the draft hood though, as some fraction of the flue gas may still be spilling. When the chimney pressure is positive relative to the chamber, air is flowing from the chimney into the chamber and spillage or backdrafting is occurring. Since the dilution air temperature approach is a more direct measure of whether spillage is occurring or not, this was used as the primary detection method. This approach was found to provide detection accuracy and response time as good, or better, than the conventional smoke visualization approach.

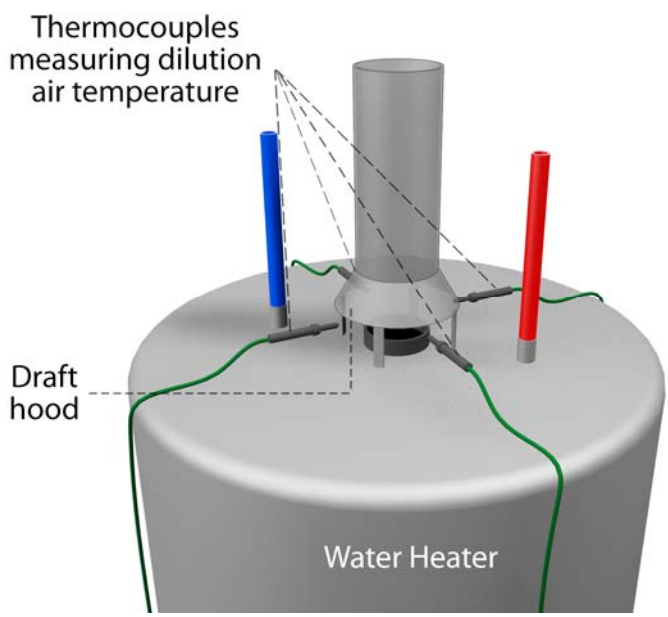

Fig. 6. Schematic representation of the thermocouples used for CVEP and WVMD testing in the "dilution air temperature" approach.

3.2 PERFORMANCE METRIC MEASUREMENT APPROACH

The measured value of CVEP equals the lowest depressurization level at which the appliance still has the ability to establish an upward natural draft through a downdrafting cold vent. The CVEP is determined by depressurizing the test chamber to a level where spillage will occur and then starting the gas-fired appliance(s) with an unheated vent. The chamber depressurization is then incrementally and gradually decreased (aka the chamber pressure is increased) until the equipment begins drafting. Onset of drafting is detected using the dilution air temperature method described previously.

Figure 7 presents measured 5-second averaged data (data were sampled at 5 Hz and averaged over a 5-second interval to smooth the low differential pressure measurements), illustrating the dilution air temperature method for detecting the onset of drafting to determine the value of CVEP in pascals. The precipitous drop in dilution air temperature (solid blue line) indicates when spillage stops and the transition to proper drafting occurs. This transition is marked with the vertical dotted line. CVEP is determined at the intersection of the vertical dotted line with measured chamber depressurization (solid purple line). The CVEP value is –2.0 Pa as highlighted by the dotted horizontal line. The average chimney and outdoor temperatures at the transition are also determined by the intersections of the trend lines of these data with the vertical dotted line.

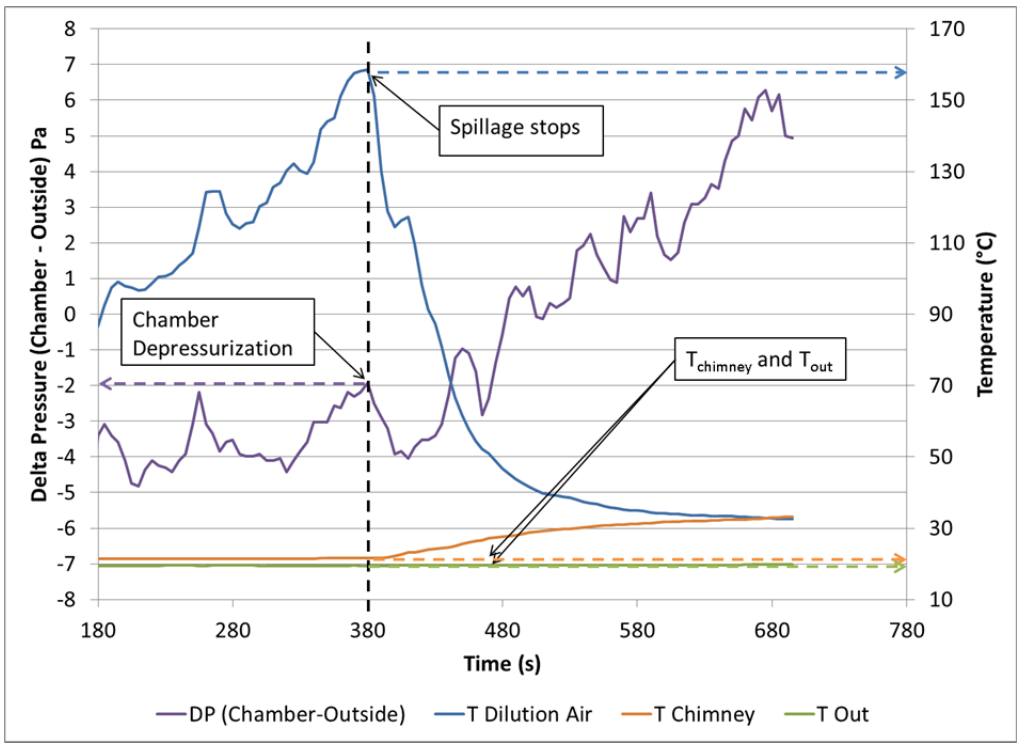

Fig. 7. Data illustrating the dilution air temperature method for determining the value of CVEP.

The measured value of WVMD equals the lowest depressurization level at which a steadily operating appliance on a warm vent still has the ability to maintain a draft without spilling. The WVMD is determined by monitoring the chimney temperatures to determine when steady-state conditions are achieved, while holding the chamber at approximately 0 Pa differential pressure relative to the outdoors and operating the gas-fired appliance(s). The chamber is then slowly depressurized until the onset of

backdrafting or spillage is detected using the dilution air temperature and chimney pressure methods described previously.

Figure 8 presents measured 5-second averaged data illustrating the dilution air temperature method for detecting the onset of spillage to determine the value of WVMD in Pa. The precipitous rise in dilution air temperature (solid blue line) indicates when spillage begins and the transition to improper drafting occurs. This transition is marked with the vertical dotted line. WVMD is determined at the intersection of the vertical dotted line with measured chamber depressurization (solid purple line). The WVMD value is -3.9 Pa, as highlighted by the dotted horizontal line. The average chimney and outdoor temperatures at the transition are also determined by the intersections of the trend lines of these data with the vertical dotted line.

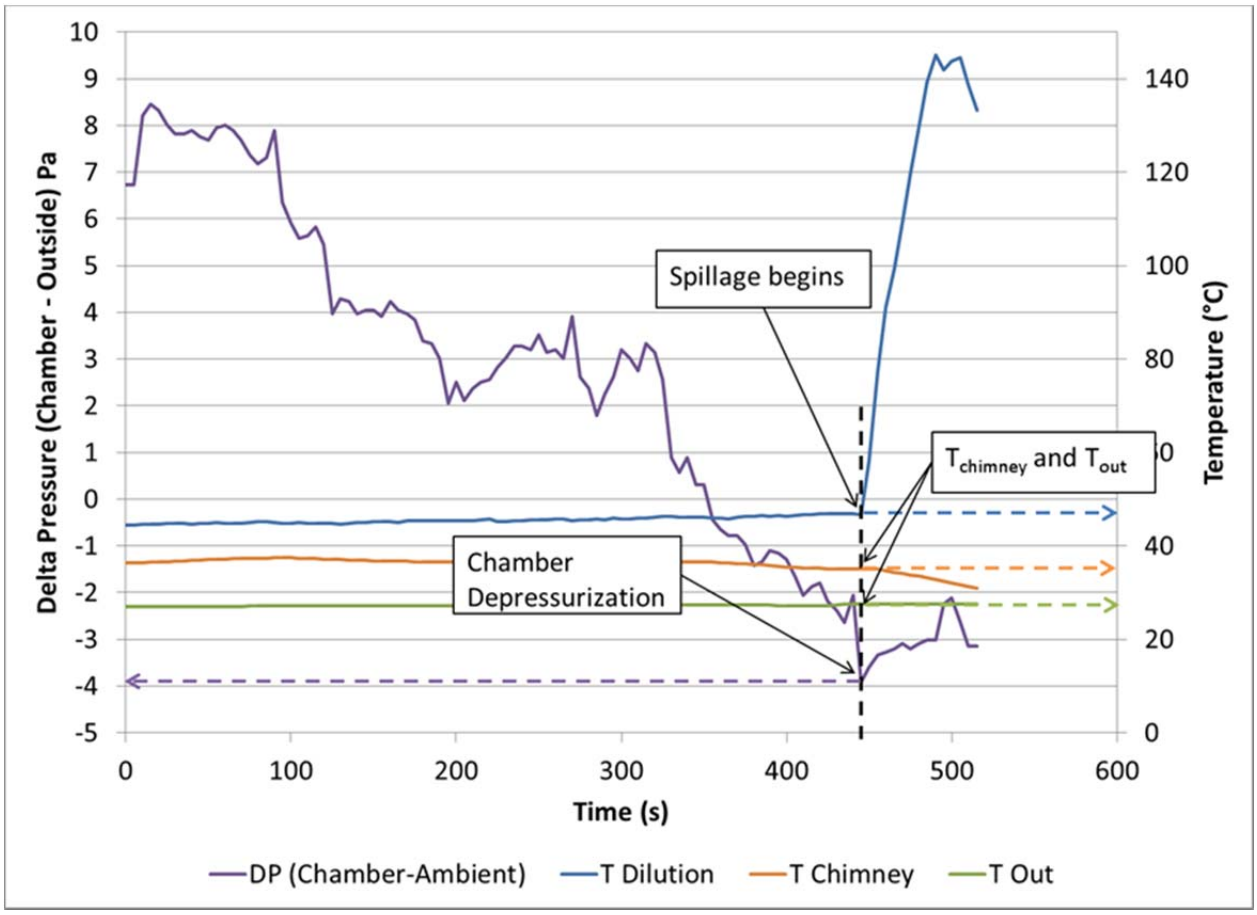

Fig. 8. Data illustrating the dilution air temperature method for determining the value of WVMD.

3.3 VENT PERFORMANCE EVALUATION APPROACH

One possible means of evaluating vent performance involves comparing the measured CVEP and WVMD depressurization values with existing depressurization tests. For example, a recent study at Lawrence Berkeley National Laboratory (Rapp et al. 2012) identified the Building Performance Institute (BPI) depressurization test for buildings. The 2012 version of the BPI guidelines provides maximum residential appliance zone depressurization limits for various natural draft appliances as listed in Table 1 (BPI 2012).

For clarity, the BPI document describes how to go to a building and conduct a test of the building. In simple terms, one turns on all the exhaust fans and measures depressurization in the vicinity of the gas-fired appliance. So, in reference to Table 1, it would be desirable if the measured pressure in the vicinity of an orphaned water heater were higher than the maximum depressurization limit of -2 Pa (for example, -1.8 Pa).

Table 1. BPI combustion appliance zone depressurization limits for natural draft appliances (BPI 2012)

Description of appliance	Maximum building depressurization limit (Pa)
Orphaned water heater	-2
Boiler or furnace common-vented with a water heater	-3
Boiler or furnace with a vent damper common-vented with a water heater	-5

Table 1 is for the building, not for the various appliance and venting system combinations in the building. However, the authors continued to pursue the theory that the maximum combustion air zone depressurization limits therein might still provide useful comparisons to measured CVEP and WVMD depressurization values for specific appliance and venting system configurations. Building off of the previous BPI example, if the house containing the orphaned water heater has a pressure above -2 Pa (e.g., -1.8 Pa) in the vicinity of the water heater and the measured CVEP of the orphaned water heater on the chimney is lower than -2 Pa (actually lower than -1.8 Pa for that specific house), one could argue that the orphaned water heater should reliably establish a draft through a cold vent.

An issue with the BPI test, and for that matter the definitions of CVEP and WVMD, is that the outdoor air temperature (OAT), and therefore the temperature difference (or ΔT, equal to the average bottom-to-top chimney temperature minus OAT), is not specified. The experimental results reported here indicate that CVEP and WVMD values depend on ΔT. The authors also suspect (but have not verified) that depressurization values in the vicinity of the gas-fired appliance, measured in accordance with BPI in the same building but on different days, would have a modest dependence on the prevailing ΔT at the time of the tests.

For these reasons the authors have discounted comparison of measured CVEP and WVMD with Table 1 as the primary evaluation approach. Discounting the use of the BPI table is consistent with BPI's own actions since the soon to be published 2014 update (BPI 2014) to their test protocol no longer includes the table providing combustion appliance zone depressurization limits for natural-draft appliances. Instead, in this study the experimental data have been used to determine simple mathematical relationships between measured values of CVEP and WVMD and a dimensionless temperature explained shortly. Then, for the purposes of this work, reasonable values for dimensionless temperature have been specified, enabling determination of CVEP and WVMD for operating conditions deemed most critical on a consistent basis. This consistency allows the performance of venting system solutions to be evaluated by comparing their measured values of CVEP and WVMD with those of the matching baseline venting system.

Nondimensional temperature or $\Delta T/T$ equals average chimney temperature minus OAT in kelvins (note: temperature differences in kelvins and degrees Celsius are identical) divided by average chimney temperature in kelvins. Pressure difference or ΔP (aka chamber depressurization) equals chamber pressure minus outdoor pressure in pascals. Simple theory (see Appendix A) tells us that the transition from improper to proper drafting regimes occurs along a straight line when $\Delta T/T$ is plotted versus ΔP. Since CVEP and WVMD are both measures of this transition, their data can be plotted together on $\Delta T/T$ versus

ΔP coordinates. This generates a triangle-shaped plot sometimes referred to as a "triangle plot" in this report.

Test data associated with a baseline configuration where a noncondensing furnace and an atmospheric water heater are common-vented through a clay tile–lined masonry chimney are presented in Fig. 9. Specifically, CVEP and WVMD data are presented for the case of water heater–only operation (aka furnace idle). Blue dots represent the results of three CVEP tests taken under different operating conditions (aka different average chimney and outdoor temperatures). In simple terms, three Fig. 7s were used to generate the CVEP data shown in Fig. 9. Likewise, orange squares represent the results of ten WVMD tests taken under different operating conditions. In other words, ten Fig. 8s were used to generate the WVMD data shown in Fig. 9.

The line defined by linear regression of the CVEP and WVMD data in Fig. 9 defines the baseline venting system performance for water heater–only operation on the masonry chimney. Now any solution that enables a condensing furnace and atmospheric water heater to vent through this same masonry chimney can have its water heater–only venting performance evaluated by comparison with Fig. 9.

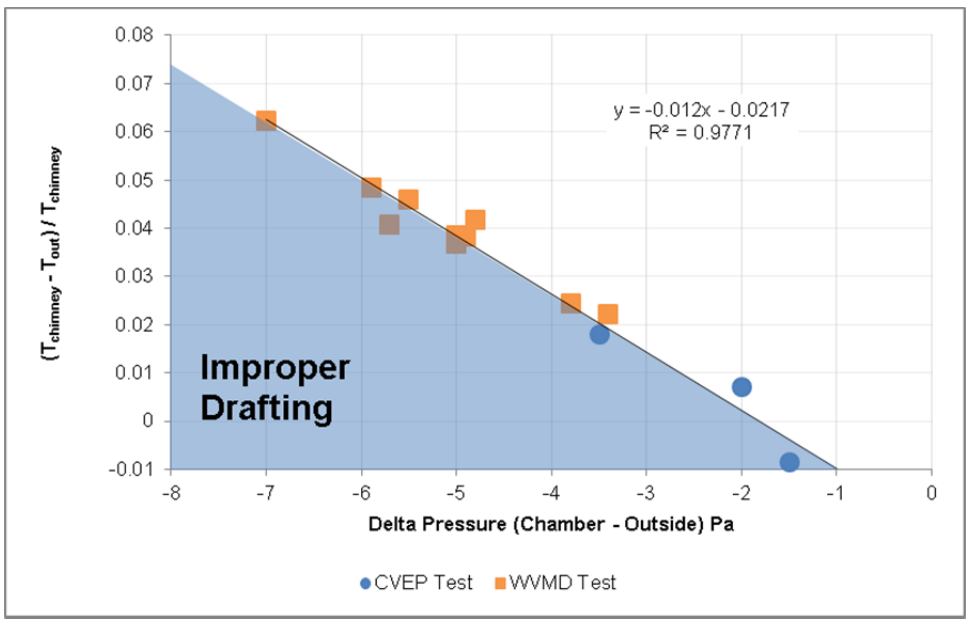

Fig. 9. CVEP and WVMD for baseline water heater–only operation on the masonry chimney.

For example, suppose a retrofit is implemented that involves replacing the noncondensing furnace with a condensing one and installing the M&G DuraVent single-flex reline solution [Fig. 2(b)] into the existing chimney. The data relevant to this example are shown in Fig. 10. Again, CVEP and WVMD data are presented for the case of water heater–only operation (aka furnace idle). Blue dots represent the results of four CVEP tests taken under different operating conditions (aka different average chimney and outdoor temperatures). In simple terms, four Fig. 7s were used to generate the CVEP data shown in Fig. 10. Likewise, orange squares represent the results of thirteen WVMD tests taken under different operating conditions. In other words, thirteen Fig. 8s were used to generate the WVMD data shown in Fig. 10.

Since the Type B metal chimney was located outdoors and has minimal thermal mass, the average chimney temperature is very dependent on OAT. The lowest temperature differential between the chimney average and outdoors, observed during the CVEP experimental tests, was chosen as the ΔT for

the CVEP values used in the evaluation. This operating condition is most critical because minimum ΔT corresponds to minimum natural buoyancy drive.

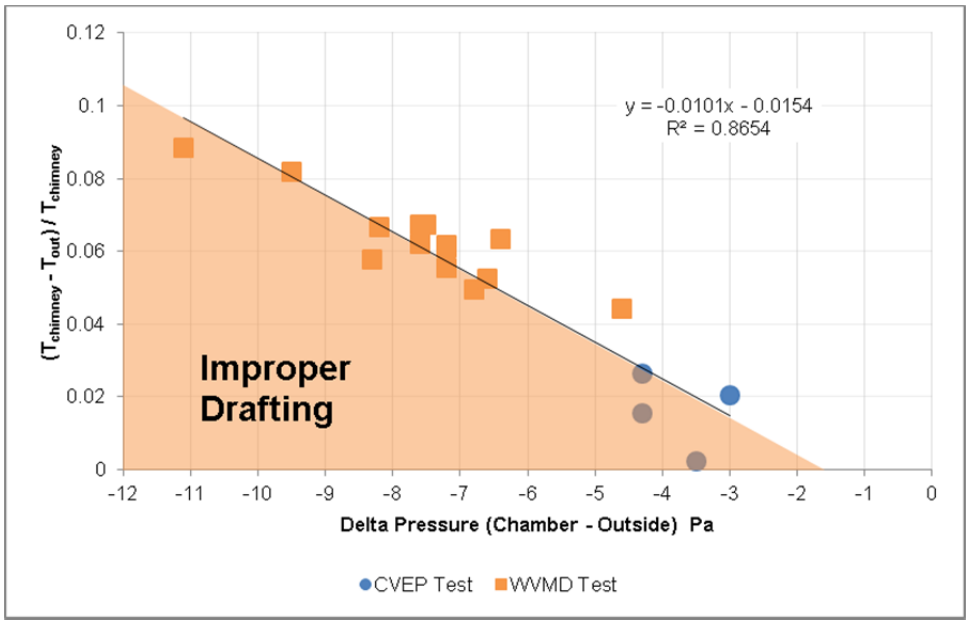

Fig. 10. CVEP and WVMD for M&G DuraVent single-flex reline solution [see Fig. 2(b)] water heater–only operation on the masonry chimney.

The masonry chimney was located inside a conditioned high bay lab except for the top few feet. Because of the indoor location and the significant thermal mass, the average chimney temperature was observed to be much less dependent on the OAT than the Type B metal chimney located outside. Where feasible, multiple CVEP test points were used to generate a linear relationship between the average chimney temperature during the CVEP test and the OAT. This relationship was then used to determine what the average chimney temperature would have been if the CVEP test were run at the OAT selected for the baseline versus solution comparison (21°C or 14°C, as explained later). Figure 11 presents an example of this type of data.

In a few operational cases, insufficient masonry chimney CVEP test data were available to generate a robust linear trend between the average chimney temperature and the OAT like that shown in Fig. 11. In these cases, the average chimney temperature was assumed to be the same as that of the most similar test case (e.g., insufficient data for a furnace-only test case meant that the water heater + furnace average chimney temperature was used). Since this is a measure of the average chimney temperature during downdrafting or backdrafting, the appliances operating will have only minimal impact on the overall average chimney temperature.

In most locales during spring, summer, and fall, the water heater will be working alone to either establish a draft in a cold vent (CVEP) or maintain a draft in a warm vent (WVMD). For this operating case, the OAT was fixed at 21°C (69.8°F) to represent a typical warm weather condition. For cases when a furnace was operating, the OAT was set to 14°C (57.2°F), representing mild heating season conditions that might occur during shoulder months, on the basis that severe heating conditions have strong natural buoyancy drive. These OAT selections were used for both CVEP and WVMD determinations.

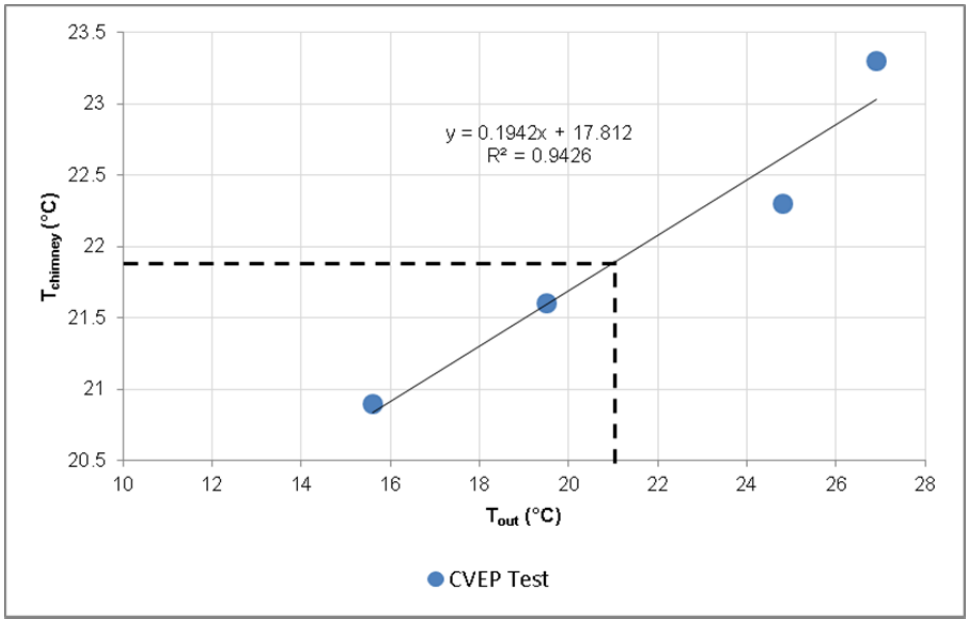

Fig. 11. Relationship between average chimney temperature and outdoor air temperature during baseline water heater–only CVEP tests on the masonry chimney.

Variations in the measured average chimney temperature between the various combinations of chimney type and operational cases are expected and were observed in the WVMD tests. All other things being equal, chimney temperature when one appliance is operating will be lower than when both are operating. Likewise, chimney temperature when a noncondensing furnace is operating will be higher than when a condensing furnace is operating. This diversity of average chimney temperatures suggests that selecting one for all baseline and solution cases would be unwise. Since the WVMD metric concerns sustaining a warm vent during ongoing appliance operation, it was decided—for average chimney temperature—to choose the highest value observed in the data for each test case. These generally corresponded to the longest duration tests.

The OAT and average chimney temperature selections for CVEP and WVMD described above enable the calculation of dimensionless temperature for the various cases. Then Figs. 9 and 10 (and similar pairs of figures for the other cases) can be used to determine the CVEP and WVMD values for inclusion in the final venting performance comparison tables. To illustrate how this is done we overlay Figs. 9 and 10, as illustrated in Fig. 12. For WVMD for the water heater–only baseline, the maximum average chimney temperature observed in the data was 313.6 K (40.4°C) so that with the OAT fixed at 294.2 K (21°C), $\Delta T/T$ becomes 0.062 [(313.6–294.2)/313.6]. For the M&G DuraVent single reline solution, the value of $\Delta T/T$ is 0.052 [(310.4–294.2)/310.4]. The WVMD values are determined by projecting horizontal dotted lines from $\Delta T/T$ to where they intersect with the baseline or solution lines, which mark the transition between improper and proper drafting. For CVEP for the water heater–only baseline, the OAT is fixed at 294.2 K (21°C). The average chimney temperature at an OAT of 294.2 K (21°C) is determined from Fig. 11 to be 295.1 K (21.9°C); therefore, $\Delta T/T$ equals 0.003 [(295.1–294.2)/295.1]. Likewise for the single reline solution, $\Delta T/T$ equals 0.005. As with WVMD, the CVEP values are determined by projecting dotted lines.

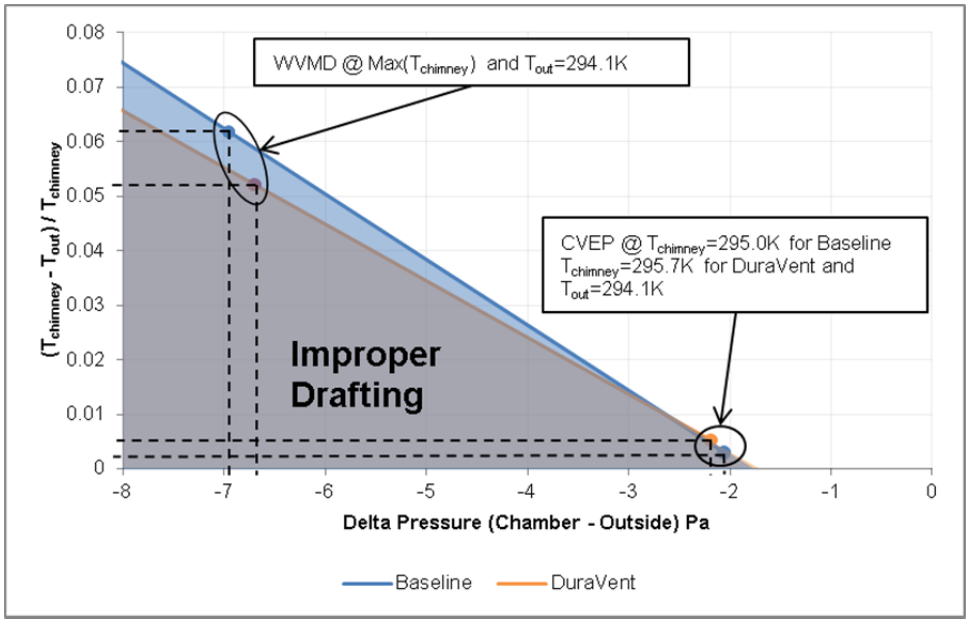

Fig. 12. Determination of CVEP and WVMD from baseline and M&G DuraVent single-flex reline solution [see Fig. 2(b)] water heater–only test data for the masonry chimney.

Table 2 provides a presentation of the summary comparison of the baseline and the M&G DuraVent single-flex reline solution in the masonry chimney. The baseline configuration is a noncondensing furnace and an atmospheric water heater common-vented through the masonry chimney. The retrofit that converts from the baseline to the prospective solution involves installing a condensing furnace in place of the noncondensing one and installing the M&G DuraVent single-flex reline solution into the existing chimney so that both appliances can vent through it. Note that CVEP and WVMD are performance indicators for Category I appliance vents only, so the values listed for "prospective solution—water heater plus condensing furnace" are referring to the water heater portion of the venting solution (the condensing furnace portion is power-vented, resulting in "no spillage or backdraft" by definition).

Table 2 would be interpreted as follows. Based on comparison of WVMD values with the maximum building depressurization limits in Table 1, it can be concluded that all of the baseline and prospective solution cases have far more capability than needed to sustain draft on a warm vent. Previously we said this type of comparison was "discounted" because the ΔT associated with Table 1 is unknown, but here the WVMD values are so far in excess of Table 1 that any physically possible ΔT could not reverse this conclusion. The most challenging metric is always CVEP (establishing a draft through a cold downdrafting vent). The case of greatest concern is water heater–only operation. In this critical case—CVEP during water heater–only operation—the prospective solution performs better than the baseline. This information strongly suggests that the prospective solution would provide adequate vent performance.

The experimental data were also compared with theoretical predictions of volumetric flow up the chimney (see the simple theory in Appendix A) in an effort to add an additional level of confidence to the findings of this study. Volumetric flow of vent gases up the chimney (in cubic feet per minute, or CFM) is a function of ΔT (in degrees Celsius) and ΔP (in pascals). Figure 10 shows the measured flow through the chimney (dots), as well as the theoretically calculated flow (solid lines) for various values of ΔT and ΔP.

Table 2. CVEP and WVMD performance comparison: Masonry chimney baseline versus the M&G DuraVent single-flex reline solution [see Fig. 2(b)] installed inside the original masonry chimney

Configuration	Operating appliances	CVEP (Pa)	WVMD (Pa)
Baseline	Water heater only	–2.1 (ΔT = 0.9°C)	–7.0 (ΔT = 19.4°C)
	Water heater + noncondensing furnace	–8.6 (ΔT = 20.3°C)	–14.5 (ΔT = 44.7°C)
	Noncondensing furnace only	–7.4 (ΔT = 20.3°C)	–12.5 (ΔT = 36.4°C)
Prospective solution	Water heater only	–2.2 (ΔT = 1.6°C)	–6.7 (ΔT = 16.2°C)
	Water heater + condensing furnace	–3.5 (ΔT = 8.6°C)	–7.6 (ΔT = 22.7°C)
	Condensing furnace only	No spillage or backdraft	No spillage or backdraft

Since the measurement-derived calculation of volumetric flow up the chimney involves the use of multiple measurements of very small pressure differentials, there is a fair amount of uncertainty in this calculation. For this reason the previously described methodology for evaluating the performance of venting systems using CVEP and WVMD was deemed more reliable and repeatable for use as the primary indicator of improper drafting, and the calculation of volumetric flow from data was not directly used in the venting system evaluation. Nonetheless it is clear from Fig. 13 that the measurement and theory-derived values of volumetric flow exhibit the same general shape and trends as a function of ΔT and ΔP.

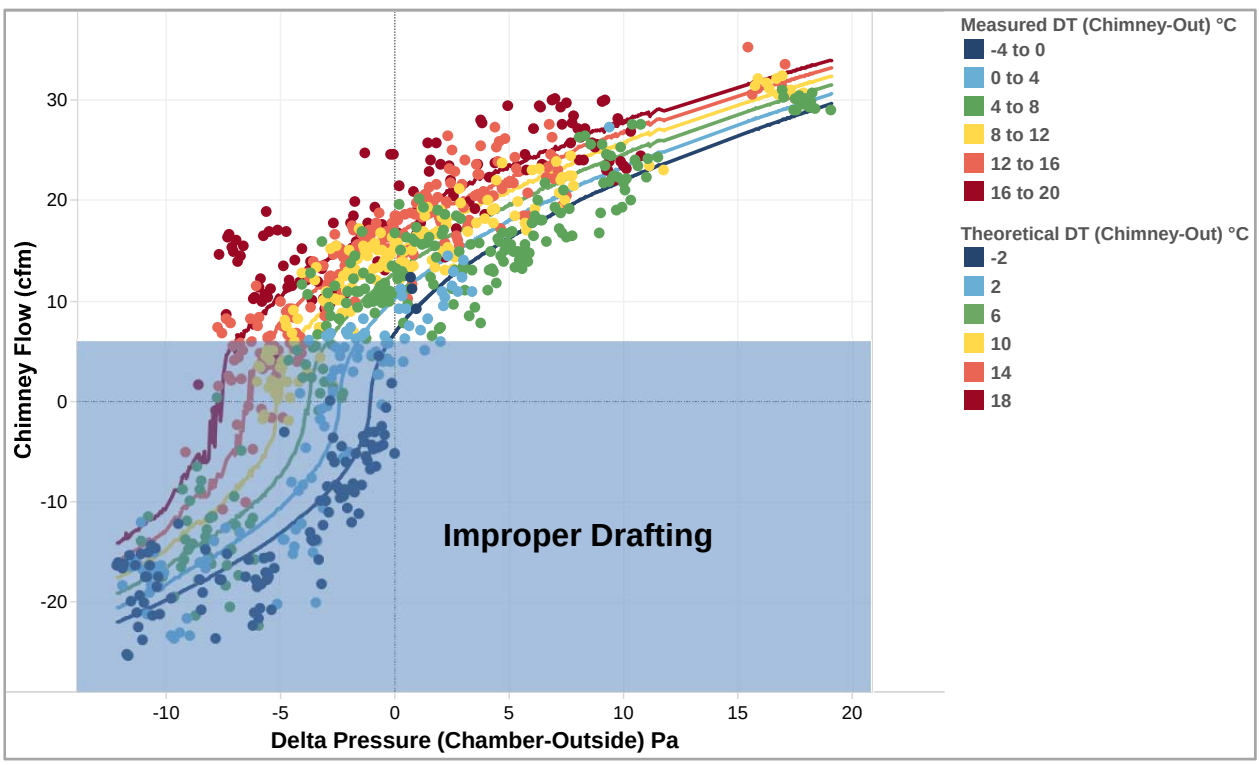

Fig. 13. Measurement and theory-derived values of volumetric flow of flue gases up the baseline masonry chimney during water heater–only operation.

4. EVALUATION RESULTS

This study experimentally evaluated five venting solutions, one for Type B metal chimneys and four for masonry chimneys. This section presents five summary CVEP and WVMD performance comparison tables. Each table presents the performance of one of the solutions compared with the performance of the baseline venting system relevant to that solution. In Sect. 5, the most relevant case from each of these five tables is summarized in one table. Details of the appliances tested, chimneys used, appliance-to-chimney vent connections, and solutions tested are presented in Appendix C.

The CVEP and WVMD values were determined experimentally, as explained in Sect. 3. In a nutshell, triangle plots with ΔT/T versus ΔP coordinates (e.g., Figs. 9 and 10) are overlaid (Fig. 12), operating conditions (outdoor temperature and average chimney temperature) deemed to be most critical for the comparative evaluation are selected, and the overlays are used to determine CVEP and WVMD values for populating the summary tables. The triangle plots used to populate the tables are presented in Appendix B. It should be noted that CVEP and WVMD are performance indicators for Category I appliance vents only, so the values listed in the tables below for "prospective solution—water heater plus condensing furnace" are referring to the water heater portion of the venting solution (the condensing furnace portion is power-vented, resulting in "no spillage or backdraft" by definition).

Table 3 presents the summary comparison of the baseline Type B metal chimney and the M&G DuraVent B Vent reline solution in the metal chimney. The baseline configuration is a noncondensing furnace and an atmospheric water heater common-vented through the metal chimney. The retrofit that converts from the baseline to the solution involves installing a condensing furnace in place of the noncondensing one and installing the B Vent reline solution (see Fig. 1) into the existing metal chimney so that both appliances can vent through it. Based on comparison of WVMD values with the maximum building depressurization limits in Table 1, it can be concluded that all of the baseline and solution cases have far more capability than needed to sustain draft on a warm vent. In the most challenging case—CVEP during water heater–only operation—the solution performs better than the baseline.

Table 3. CVEP and WVMD performance comparison: Type B metal chimney baseline versus the M&G DuraVent B Vent reline solution (see Fig. 1) installed inside the original Type B metal chimney

Configuration	Operating appliances	CVEP (Pa)	WVMD (Pa)
Baseline	Water heater only	–1.5 (ΔT = 0°C)	–11.0 (ΔT = 57.7°C)
	Water heater + noncondensing furnace	–5.3 (ΔT = 28.7°C)	–15.3 (ΔT = 99.8°C)
	Noncondensing furnace only	–4.2 (ΔT = 28.7°C)	–15.9 (ΔT = 91°C)
Prospective solution	Water heater only	–2.6 (ΔT = 4.1°C)	–12.1 (ΔT = 65.2°C)
	Water heater + condensing furnace	–4.1 (ΔT = 7.8°C)	–12.7 (ΔT = 65.3°C)
	Condensing furnace only	No spillage or backdraft	No spillage or backdraft

Table 4 presents the summary comparison of the baseline masonry chimney and the M&G DuraVent dual-flex reline solution in the masonry chimney. The baseline configuration is a noncondensing furnace and an atmospheric water heater common-vented through the masonry chimney. The retrofit that converts from the baseline to the solution involves installing a condensing furnace in place of the noncondensing one and installing the dual-flex reline solution [see Fig. 2(a)] into the existing masonry chimney so that

both appliances can vent through it. Based on comparison of WVMD values with the maximum building depressurization limits in Table 1, it can be concluded that all of the baseline and solution cases have far more capability than needed to sustain draft on a warm vent. In the most challenging case—CVEP during water heater–only operation—the solution performs better than the baseline.

Table 4. CVEP and WVMD performance comparison: masonry chimney baseline versus the M&G DuraVent dual-flex reline solution [see Fig. 2(a)] installed inside the original masonry chimney

Configuration	Operating appliances	CVEP (Pa)	WVMD (Pa)
Baseline	Water heater only	–2.1 (ΔT = 0.9°C)	–7.0 (ΔT = 19.4°C)
	Water heater + noncondensing furnace	–8.6 (ΔT = 20.3°C)	–14.5 (ΔT = 44.7°C)
	Noncondensing furnace only	–7.4 (ΔT = 20.3°C)	–12.5 (ΔT = 36.4°C)
Prospective solution	Water heater only	–2.4 (ΔT = 4.4°C)	–11.8 (ΔT = 53.9°C)
	Water heater + condensing furnace	Same as water heater only[1]	Same as water heater only[1]
	Condensing furnace only	No spillage or backdraft	No spillage or backdraft

[1]In the dual-flex reline solution, the water heater and condensing furnace have separate, dedicated liners. Therefore, no venting interaction is expected between the water heater and the condensing furnace.

Table 5 presents the summary comparison of the baseline masonry chimney and the M&G DuraVent single-flex reline solution in the masonry chimney. The baseline configuration is a noncondensing furnace and an atmospheric water heater common-vented through the masonry chimney. The retrofit that converts from the baseline to the solution involves installing a condensing furnace in place of the noncondensing one and installing the single-flex reline solution [see Fig. 2(b)] into the existing masonry chimney so that both appliances can vent through it. Based on comparison of WVMD values with the maximum building depressurization limits in Table 1, it can be concluded that all of the baseline and solution cases have far more capability than needed to sustain draft on a warm vent. In the most challenging case—CVEP during water heater–only operation—the solution performs better than the baseline.

Table 5. CVEP and WVMD performance comparison: masonry chimney baseline versus the M&G DuraVent single-flex reline solution [see Fig. 2(b)] installed inside the original masonry chimney

Configuration	Operating appliances	CVEP (Pa)	WVMD (Pa)
Baseline	Water heater only	–2.1 (ΔT = 0.9°C)	–7.0 (ΔT = 19.4°C)
	Water heater + noncondensing furnace	–8.6 (ΔT = 20.3°C)	–14.5 (ΔT = 44.7°C)
	Noncondensing furnace only	–7.4 (ΔT = 20.3°C)	–12.5 (ΔT = 36.4°C)
Prospective solution	Water heater only	–2.2 (ΔT = 1.6°C)	–6.7 (ΔT = 16.2°C)
	Water heater + condensing furnace	–3.5 (ΔT = 8.6°C)	–7.6 (ΔT = 22.7°C)
	Condensing furnace only	No spillage or backdraft	No spillage or backdraft

Table 6 presents the summary comparison of the baseline masonry chimney and the fan-assisted water heater dual-reline solution in the masonry chimney. The baseline configuration is a noncondensing furnace and an atmospheric water heater common-vented through the masonry chimney. The retrofit that converts from the baseline to the solution involves installing a condensing furnace in place of the noncondensing one and installing the fan-assisted water heater dual-reline solution (see Fig. 3) into the existing masonry chimney so that both appliances can vent through it. Since this solution results in two positive-pressure ventilated appliances, no backdrafting or spillage is possible and the solution, therefore, performs better than the baseline.

Table 6. CVEP and WVMD performance comparison: masonry chimney baseline versus the fan-assisted water heater dual-reline solution (see Fig. 3) installed inside the original masonry chimney

Configuration	Operating appliances	CVEP (Pa)	WVMD (Pa)
Baseline	Water heater only	–2.1 (ΔT = 0.9°C)	–7.0 (ΔT = 19.4°C)
	Water heater + noncondensing furnace	–8.6 (ΔT = 20.3°C)	–14.5 (ΔT = 44.7°C)
	Noncondensing furnace only	–7.4 (ΔT = 20.3°C)	–12.5 (ΔT = 36.4°C)
Prospective solution	Water heater only	No spillage or backdraft	No spillage or backdraft
	Water heater + condensing furnace	No spillage or backdraft	No spillage or backdraft
	Condensing furnace only	No spillage or backdraft	No spillage or backdraft

Table 7 presents the summary comparison of the baseline masonry chimney and the EntrainVent single-reline solution in the masonry chimney. The baseline configuration is a noncondensing furnace and an atmospheric water heater common-vented through the masonry chimney. The retrofit that converts from the baseline to the solution involves installing a condensing furnace in place of the noncondensing one and installing the EntrainVent single-reline solution (see Fig. 5) into the existing masonry chimney so that both appliances can vent through it. Based on comparison of WVMD values with the maximum building depressurization limits in Table 1, it can be concluded that all of the baseline and solution cases have far more capability than needed to sustain draft on a warm vent. In the most challenging case—CVEP during water heater–only operation—the solution performs better than the baseline.

Table 7. CVEP and WVMD performance comparison: masonry chimney baseline versus the EntrainVent single-reline [chimney serviceable] solution (see Fig. 5) installed inside the original masonry chimney

Configuration	Operating appliances	CVEP (Pa)	WVMD (Pa)
Baseline	Water heater only	–2.1 (ΔT = 0.9°C)	–7.0 (ΔT = 19.4°C)
	Water heater + noncondensing furnace	–8.6 (ΔT = 20.3°C)	–14.5 (ΔT = 44.7°C)
	Noncondensing furnace only	–7.4 (ΔT = 20.3°C)	–12.5 (ΔT = 36.4°C)
Prospective solution	Water heater only	–3.7 (ΔT = 3.1°C)	–5.2 (ΔT = 14.3°C)
	Water heater + condensing furnace	–4.7 (ΔT = 10.1°C)	–6.7 (ΔT = 25°C)
	Condensing furnace only	No spillage or backdraft	No spillage or backdraft

5. CONCLUSIONS

Cost-effective, simple, and safe solutions are needed that enable condensing furnaces and atmospheric combustion water heaters to vent through the same chimney. A search for solutions was undertaken, which included efforts devoted to monitoring developments by industry and to inventing new solutions. Five prospective solutions (one for Type B metal chimneys and four for masonry chimneys) were identified that appeared cost effective and simple, and an experimental program of evaluation was undertaken to determine whether vent performance would be sufficient for them to be safe. This project provided the first in-kind full-scale chimney evaluations of the prospective solutions in an experimental facility capable of independently controlling indoor depressurization.

Section 4 presents results in the form of five tables, one for each solution. Each table covers two configurations (baseline and solution), three operating cases per configuration (water heater only, furnace and water heater, furnace only), and two performance metrics (CVEP and WVMD) for a total of twelve performance values. However, the most challenging performance metric is always CVEP, which equals the lowest depressurization level at which the gas appliance still has the capability to establish an upward draft through a downdrafting cold vent. The operating case of greatest concern for CVEP is water heater–only operation, where a gas appliance of modest capacity is working alone to establish a draft through a downdrafting cold vent. The Sect. 4 results for this case are consolidated in Table 8.

Table 8. CVEP for water heater–only operation for all baseline and solution venting system configurations experimentally evaluated in this study

Baseline chimney	Solution evaluated	Baseline CVEP (Pa)	Solution CVEP (Pa)
Type B metal chimney in good condition	M&G DuraVent B Vent reline (see Fig. 1)	–1.5 (ΔT = 0°C)	–2.6 (ΔT = 4.1°C)
Masonry chimney in bad or good condition	M&G DuraVent dual-flex reline [see Fig. 2(a)]	–2.1 (ΔT = 0.9°C)	–2.4 (ΔT = 4.4°C)
Masonry chimney in good condition	M&G DuraVent single-flex reline [see Fig. 2(b)]	–2.1 (ΔT = 0.9°C)	–2.2 (ΔT = 1.6°C)
Masonry chimney in bad or good condition	Fan-assisted water heater dual reline (see Fig. 3)	–2.1 (ΔT = 0.9°C)	No spillage or backdraft
Masonry chimney in good condition	EntrainVent single reline (see Fig. 5)	–2.1 (ΔT = 0.9°C)	–3.7 (ΔT = 3.1°C)

As can be seen in Table 8, for this most challenging case—CVEP for water heater–only operation—all of the solutions evaluated had the capability to establish a draft through a downdrafting cold vent at a lower indoor depressurization level than the baseline chimney configurations. The experimental evaluation strongly suggests that all of the solutions evaluated in this study would provide adequate vent performance. At the same time, all of these solutions enable condensing furnaces and atmospheric combustion water heaters to vent through the same chimney.

It should be noted that the results summarized here address only vent performance based on full-scale chimney evaluations using an experimental facility capable of independently controlling indoor depressurization. Vent product manufacturers moving solutions to market must still make them compliant

with actual test agency vent performance standards, which follow rigorous and time-honored procedures. These additional tests verify compliance with important mechanical, aging, and other requirements not addressed in this work. Solutions that are commercialized must also be compliant with current Underwriters Laboratories and Canadian Standards Association safety standards (covering B Vent, special gas vent, B Vent/masonry relining, and appliance CSA Z21 approval standards), in addition to the National Fire Protection Association's *National Fuel Gas Code* (NFPA 2012). These vent system product certification procedures, completed by the vent product manufacturer in collaboration with accredited national test agencies, also add important standardization to the installation.

Of the five solutions evaluated here, only one is commercially available as of this writing. In January 2015 a product called FasNSeal 80/90 [similar to the M&G DuraVent B Vent reline option (Fig. 1) evaluated here] was publicly launched by M&G DuraVent at the International Air-Conditioning, Heating, Refrigerating Exposition at McCormick Place, held in conjunction with the American Society of Heating, Refrigerating and Air-Conditioning Engineers Winter Conference in Chicago. M&G DuraVent also distributed literature at the expo announcing a product under development for masonry chimneys [see Figs. 2(a) and 2(b)].

6. REFERENCES

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APPENDIX A: THEORETICAL BACKGROUND

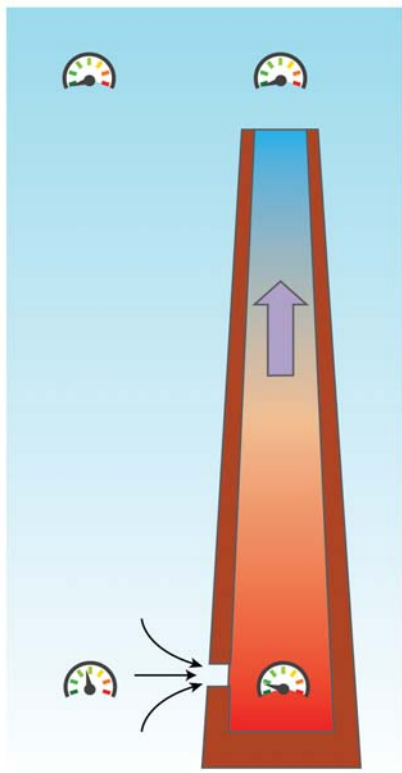
A.1 INDUCED NEGATIVE PRESSURE FOR A STAND-ALONE CHIMNEY

There is a pressure difference between the ambient air and the warmer air in the chimney, which causes air to rise through the chimney due to buoyancy forces (illustrated in Fig. A.1). That pressure difference (***ΔP***) can be calculated with Eq. A.1. For a chimney venting an appliance, where ambient air is on the outside and flue gases are on the inside, Eq. A.1 will provide only an approximation.

$$\Delta P = C_1 P_{atm} h\left(\frac{1}{T_o} - \frac{1}{T_i}\right) \quad , \tag{A.1}$$

where

ΔP = pressure potential in Pa,
C_1 = 0.0342 in K/m,
P_{atm} = atmospheric pressure in Pa,
h = height in m,
T_o = absolute outside average temperature in K,
T_i = absolute inside average temperature in K.



A.1. Schematic representation of the chimney effect in buoyancy-driven-only configuration.

A.2 INDUCED FLOW FOR A CHIMNEY

The natural draft flow rate induced by the buoyancy force for a stand-alone chimney can be calculated with Eq. A.2. (Walker 2014). For a chimney venting an appliance, where ambient air is on the outside and flue gases are on the inside, Eq. A.2 will provide only an approximation. In addition, this equation assumes frictional or transition pressure losses are zero.

$$Q = C_2 A \sqrt{2gh(\frac{T_i - T_o}{T_i})} \quad , \tag{A.2}$$

where

Q = natural draft flow rate in m^3/s,
A = flow area in m^2,
C_2 = discharge coefficient (usually taken to be from 0.65 to 0.70),
g = gravitational acceleration at 9.81 m/s^2,
h = height in m,
T_i = average inside temperature in K,
T_o = outside air temperature in K.

A.3 CHIMNEY CONNECTED TO A BUILDING OR TEST FACILITY

When a chimney is connected to a building (test facility or chamber), as shown in Fig. A.2, and the chamber is pressurized/depressurized during the experiment, the pressure level of the chamber significantly affects the drafting performance of the chimney. In addition, there is a pressure loss resulting from frictional resistance to flow through the chimney and vent connectors and transitions. For any specific vent configuration, the pressure loss will be influenced mainly by the flow rate through the chimney. The driving pressure on the flue gas is the superposition of all the applied pressures. Therefore, to account for the chamber pressure level and pressure losses in the venting system, Eq. A.1 can be modified as follows:

$$\Delta P = C_1 P_{atm} h \left(\frac{1}{T_o} - \frac{1}{T_i} \right) + (P_{cham} - P_{atm}) - P_{loss}$$

when

$$(C_1 P_{atm} h \left(\frac{1}{T_o} - \frac{1}{T_i} \right) + (P_{cham} - P_{atm})) > 0 \ , \tag{A.3}$$

or

$$\Delta P = C_1 P_{atm} h \left(\frac{1}{T_o} - \frac{1}{T_i} \right) + (P_{cham} - P_{atm}) + P_{loss}$$

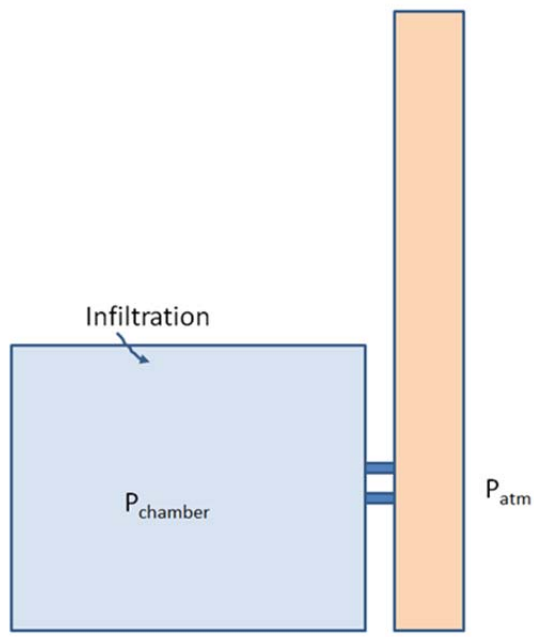
when

$$(\ C_1 P_{atm} h \left(\frac{1}{T_o} - \frac{1}{T_i} \right) + (P_{cham} - P_{atm})\ ) < 0 \ , \tag{A.4}$$

where

P_{cham} = chamber pressure in Pa.

P_{loss} = pressure loss from friction and transitions



A.2. Chimney connected to a building or test facility.

A.4 INDUCED FLOW FOR A CHIMNEY CONNECTED TO A TEST FACILITY

Considering Eqs. A.3 and A.4, the induced flow in the chimney can be approximated as

$$Q = C_2 A \sqrt{2gh\left(\frac{T_i - T_o}{T_i}\right) + \frac{2(P_{cham} - P_{atm})}{\rho_{ave}} - \frac{2P_{loss}}{\rho_{ave}}}$$

when $$(C_1 P_{atm} h\left(\frac{1}{T_o} - \frac{1}{T_i}\right) + (P_{cham} - P_{atm})) > 0, \quad \text{(A.5)}$$

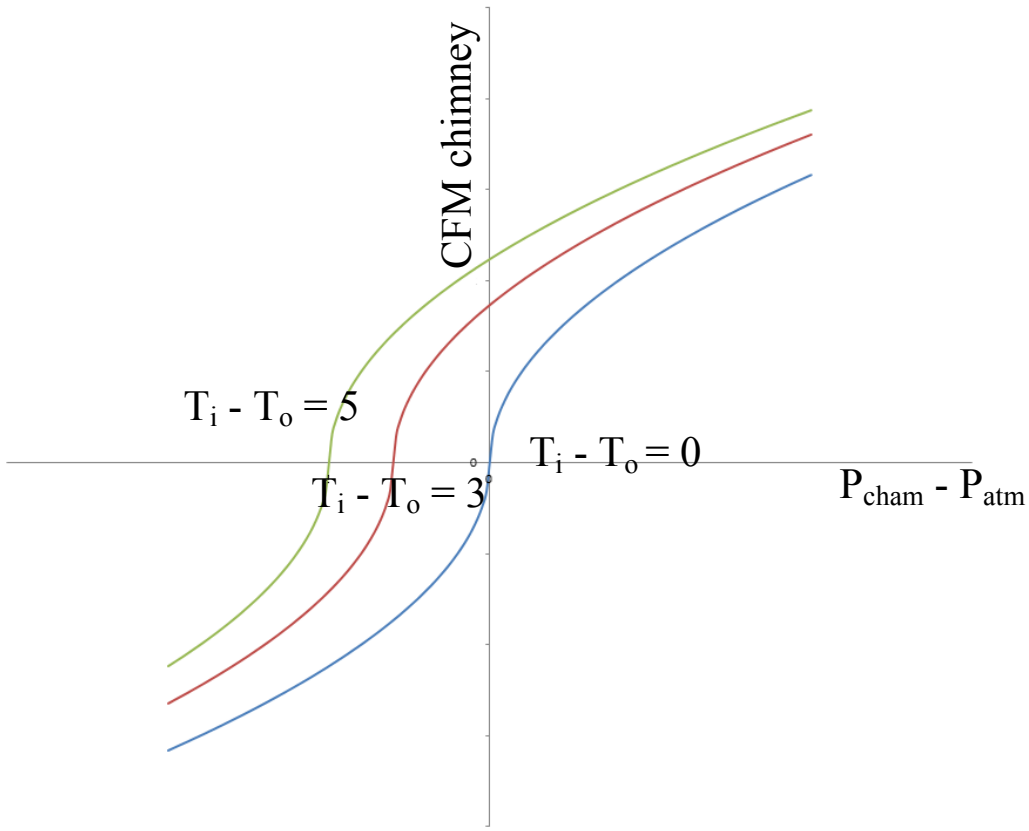
or $$Q = -C_2 A \sqrt{\left|2gh\left(\frac{T_i - T_o}{T_i}\right) + \frac{2(P_{cham} - P_{atm})}{\rho_{ave}}\right| + \frac{2P_{loss}}{\rho_{ave}}}$$

when $$(C_1 P_{atm} h\left(\frac{1}{T_o} - \frac{1}{T_i}\right) + (P_{cham} - P_{atm})) < 0, \quad \text{(A.6)}$$

where

ρ_{ave} = the average density in kg/m^3.

Figure A.3 shows hypothetical trends of the draft flow rate (Eqs. A.5 and A.6) as a function of building depressurization. This figure shows that as the building (chamber) pressure drops, a larger chimney-to-outside ΔT is needed to draft the same amount of flue gas.



A.3. A sample representation of flow vs. building-outdoor pressure differential for different chimney-ambient differential temperatures (see Eq. A.4).

A.5 TRANSITION BETWEEN PROPER AND IMPROPER DRAFTING

The chimney should provide equal or greater induced flow than the discharge flow rate of a specific appliance to prevent backdrafting or spillage. Therefore, considering Eqs. A.5 and A.6, the pressure difference between the building and atmospheric pressure at which spillage can take place can be approximated as

$$\Delta P_{\min,spill} = \frac{1}{2}\rho_{ave}\left(\frac{Q_{apl}}{C_2 A}\right)^2 - \rho_{ave} g h\left(\frac{T_i - T_o}{T_i}\right) + P_{loss} \quad , \tag{A.7}$$

where

$\Delta P_{\min,spill} = P_{cham} - P_{atm}$ = pressure difference at transition between proper and improper drafting

in Pa,

Q_{apl} = minimum appliance draft flow rate without spillage in m^3/s.

The minimum appliance draft flow rate without spillage (first term on right side of Eq. A.7) is constant for any given appliance. Hence, at transition between proper drafting and spillage, the flow through the vent, and therefore the pressure loss (third term on right side of Eq. A.7), is also constant. This means that at transition, the pressure difference required to maintain a fixed minimum draft without spillage in a specific chimney venting a specific appliance, or ΔP, has a linear relationship with the dimensionless temperature difference ΔT/T [aka, ΔP = a + b (ΔT/T)].

Figure A.4 shows a hypothetical representation of the transition between proper and improper drafting based on Eq. A.7. Since WVMD and CVEP are both measurements at the transition, their data would be expected to fall on a straight line.

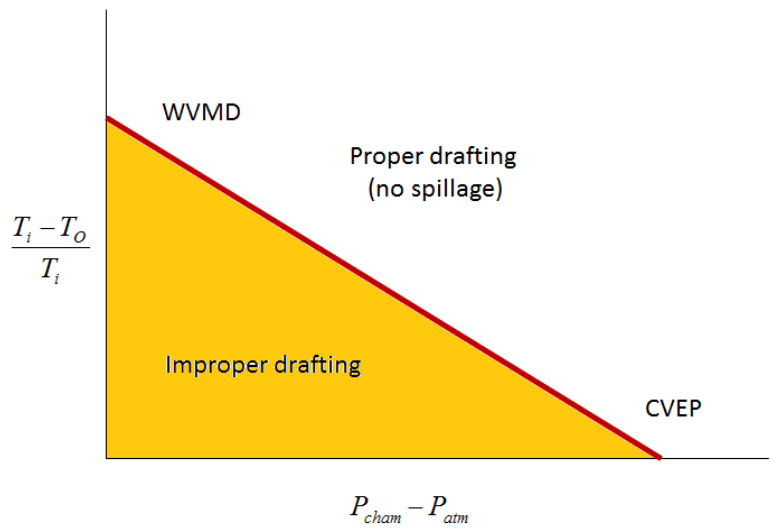


Fig. A.4. Sample representation of the transition line between proper and improper drafting as a function of dimensionless chimney temperature and building-outdoor pressure difference (see Eq. A.7).

A.6 REFERENCE

Walker, A. 2014. *Natural Ventilation*, National Renewable Energy Laboratory, Golden, Colo.

APPENDIX B: DATA SUPPORTING THE EVALUATION RESULTS

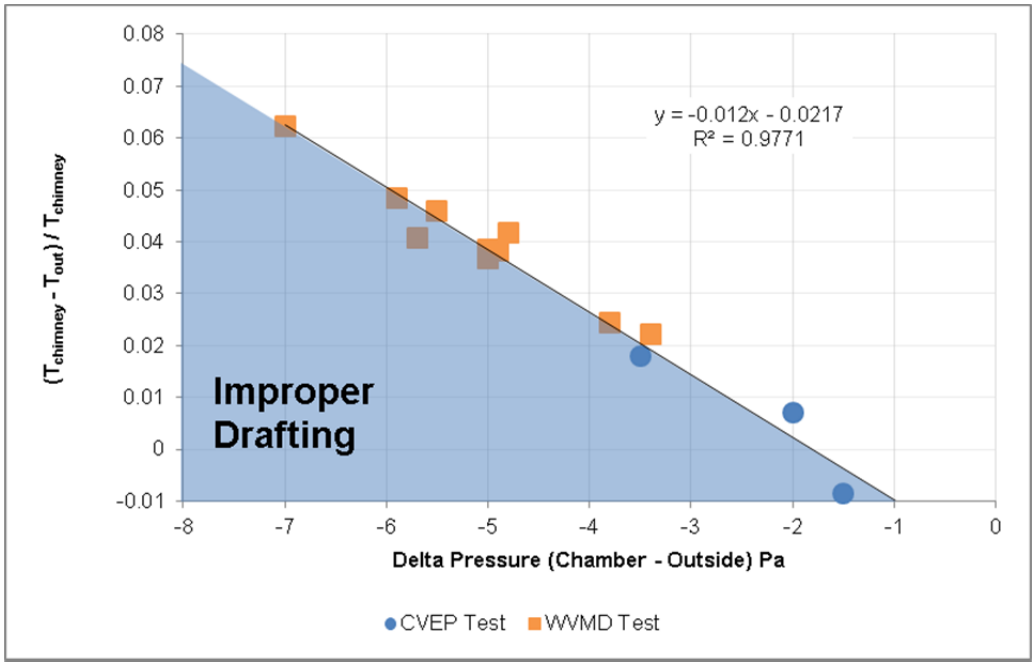


Fig. B.1. CVEP and WVMD for baseline water heater–only operation on the masonry chimney (same as Fig. 8 in Sect. 3).

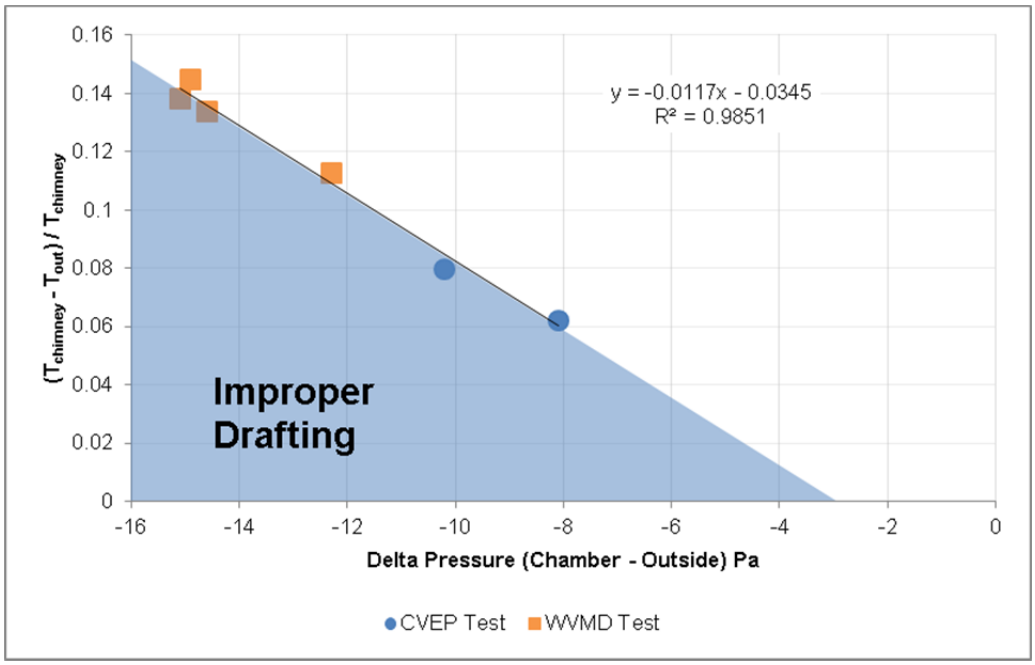


Fig. B.2. CVEP and WVMD for baseline water heater and noncondensing furnace operation on the masonry chimney.

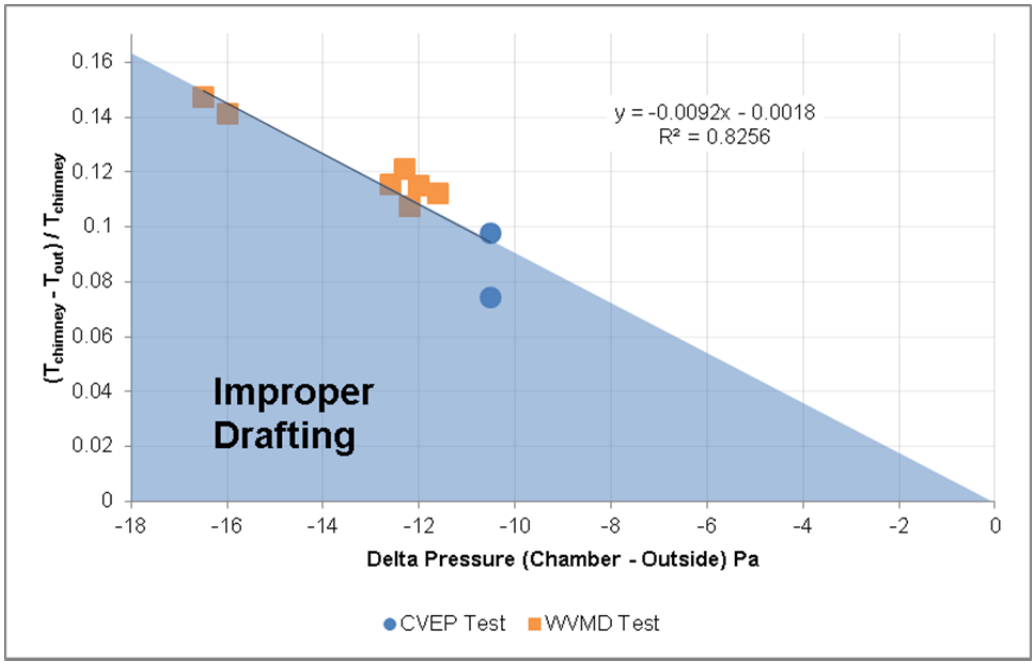


Fig. B.3. CVEP and WVMD for baseline noncondensing furnace–only operation on the masonry chimney.

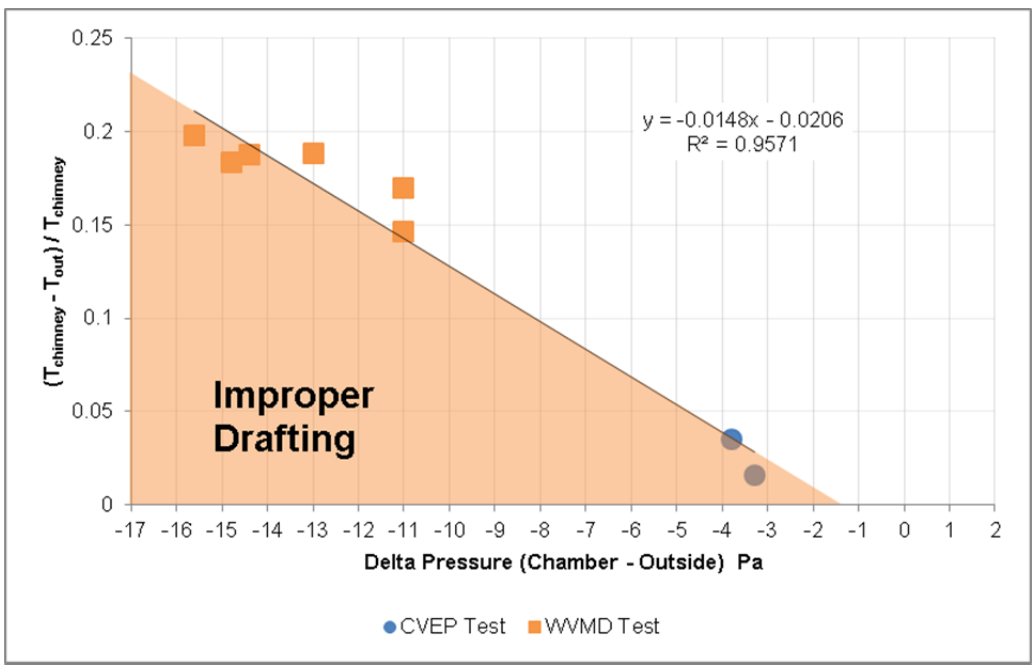


Fig. B.4. CVEP and WVMD for M&G DuraVent dual-flex reline solution [see Fig. 2(b)] water heater–only operation on the masonry chimney.

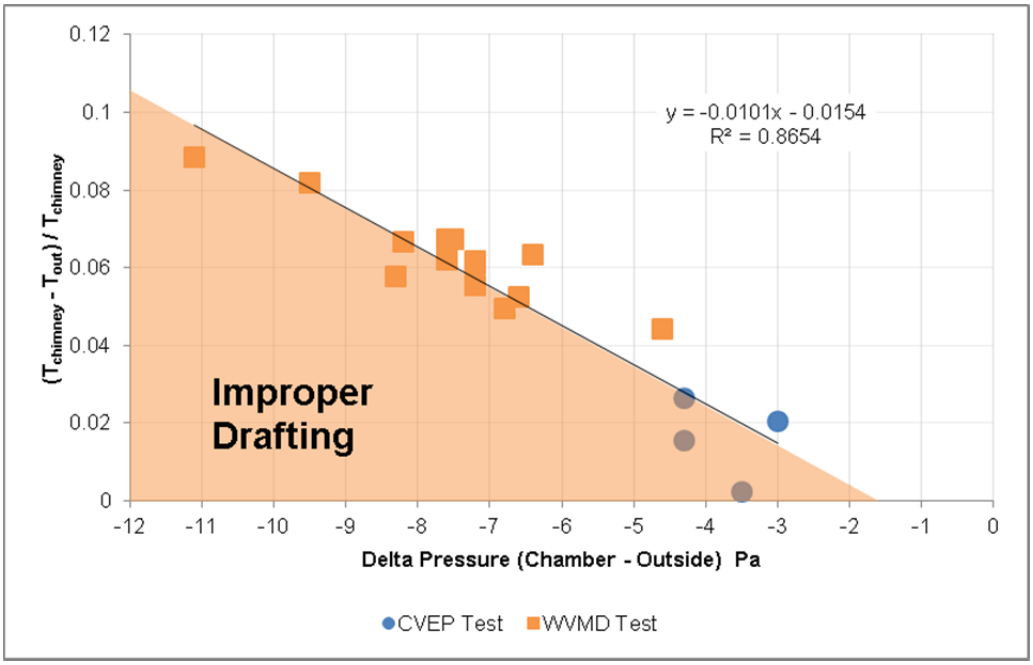


Fig. B.5. CVEP and WVMD for M&G DuraVent single-flex reline solution [see Fig. 2(b)] water heater–only operation on the masonry chimney (same as Fig. 9 in Sect. 3).

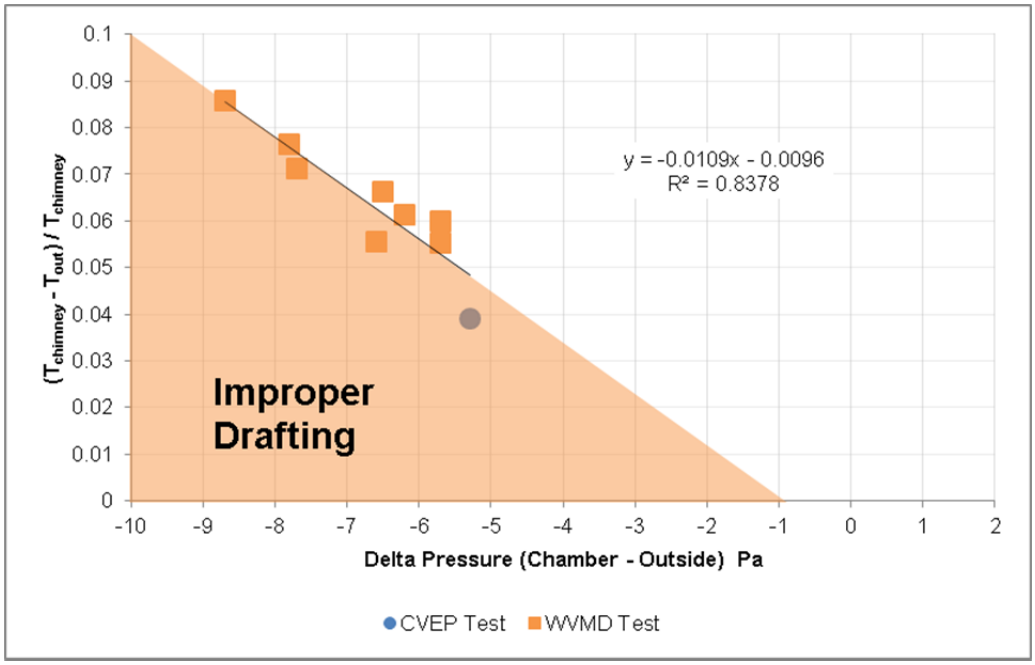


Fig. B.6. CVEP and WVMD for M&G DuraVent single-flex reline solution [see Fig. 2(b)] water heater and condensing furnace operation on the masonry chimney.

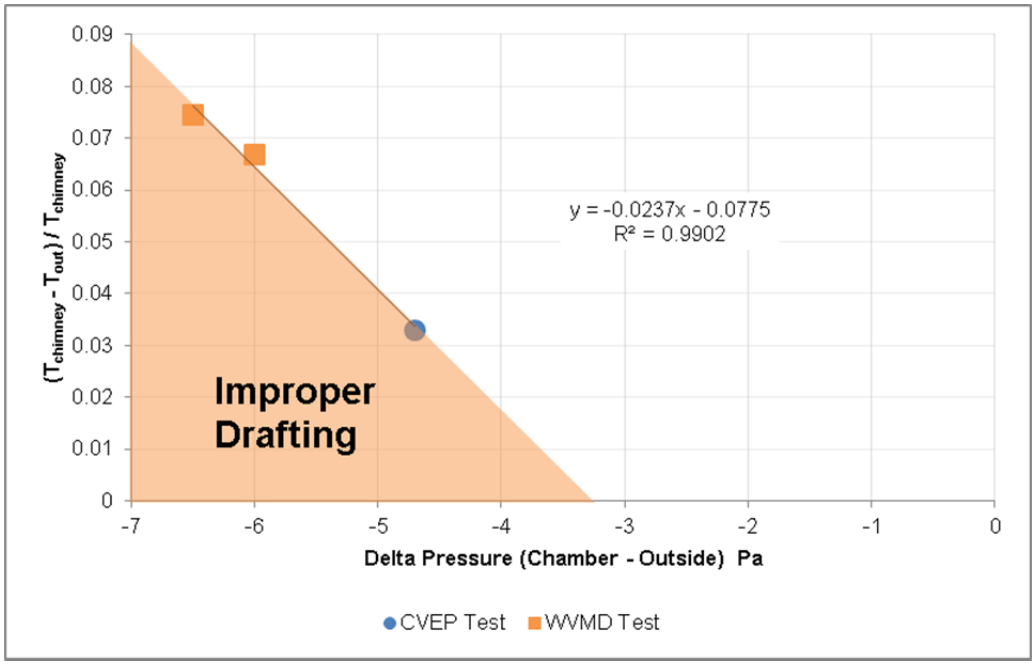


Fig. B.7. CVEP and WVMD for M&G EntrainVent single-reline solution (see Fig. 5) water heater and condensing furnace operation on the masonry chimney.

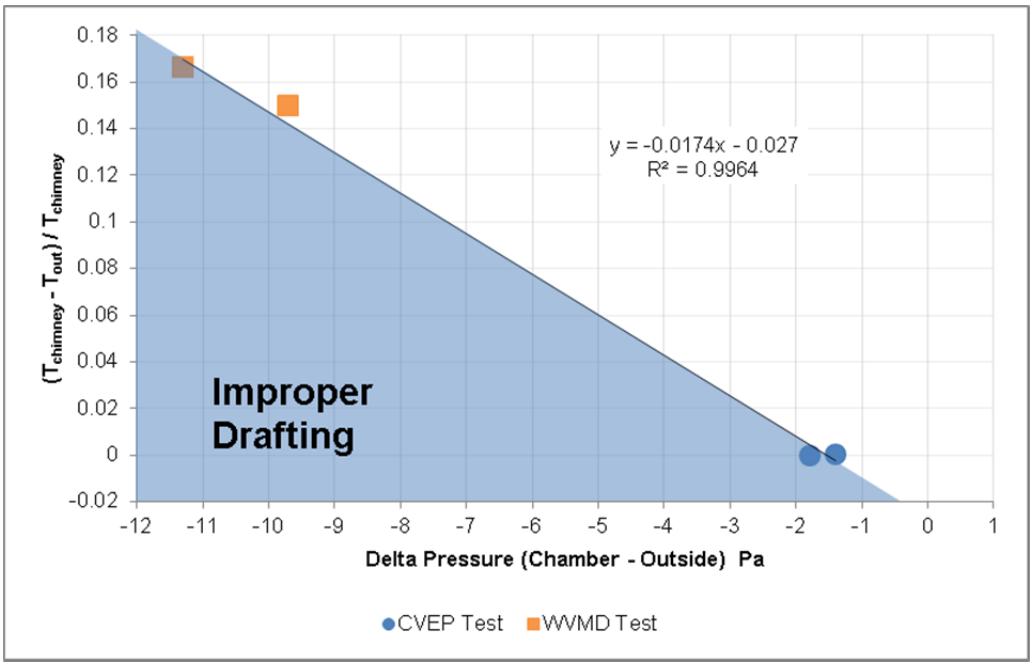


Fig. B.8. CVEP and WVMD for baseline water heater–only operation on the Type B metal chimney.

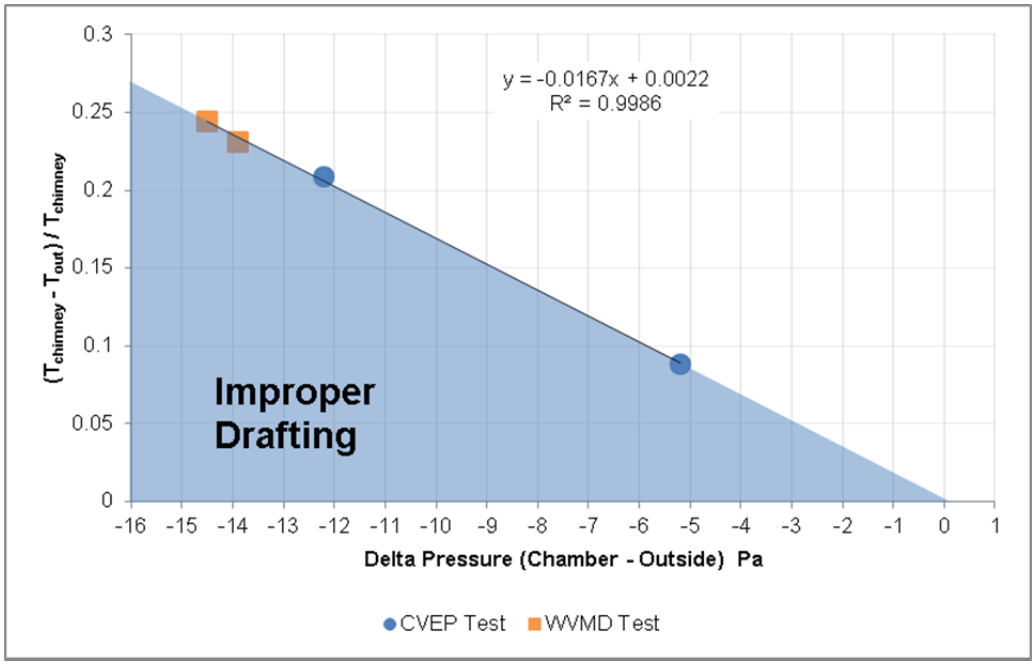


Fig. B.9. CVEP and WVMD for baseline water heater and noncondensing furnace operation on the Type B metal chimney.

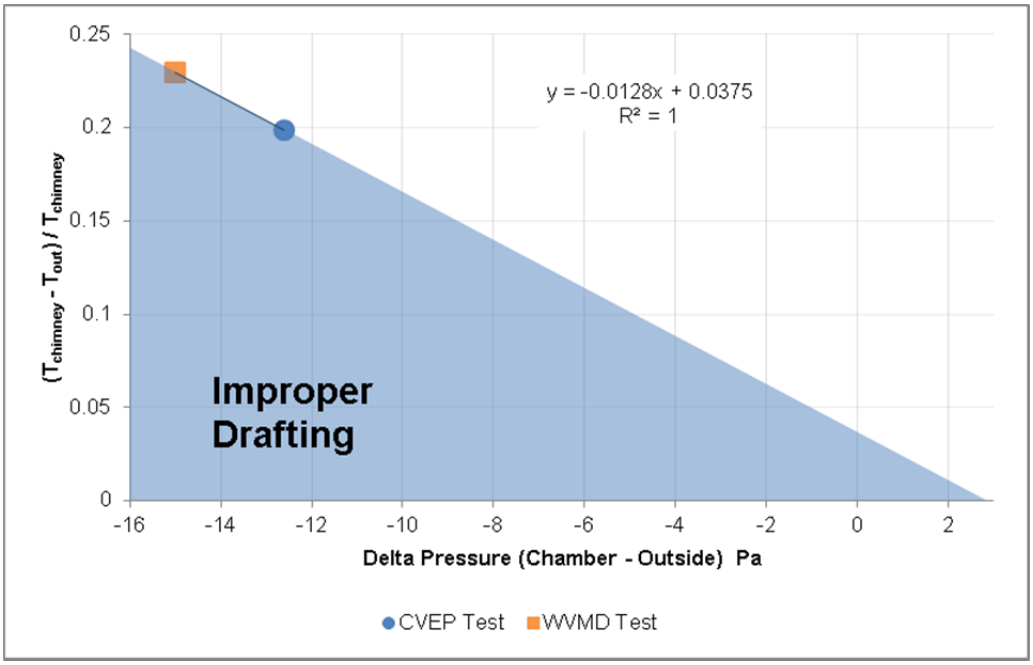


Fig. B.10. CVEP and WVMD for baseline noncondensing furnace–only operation on the Type B metal chimney.

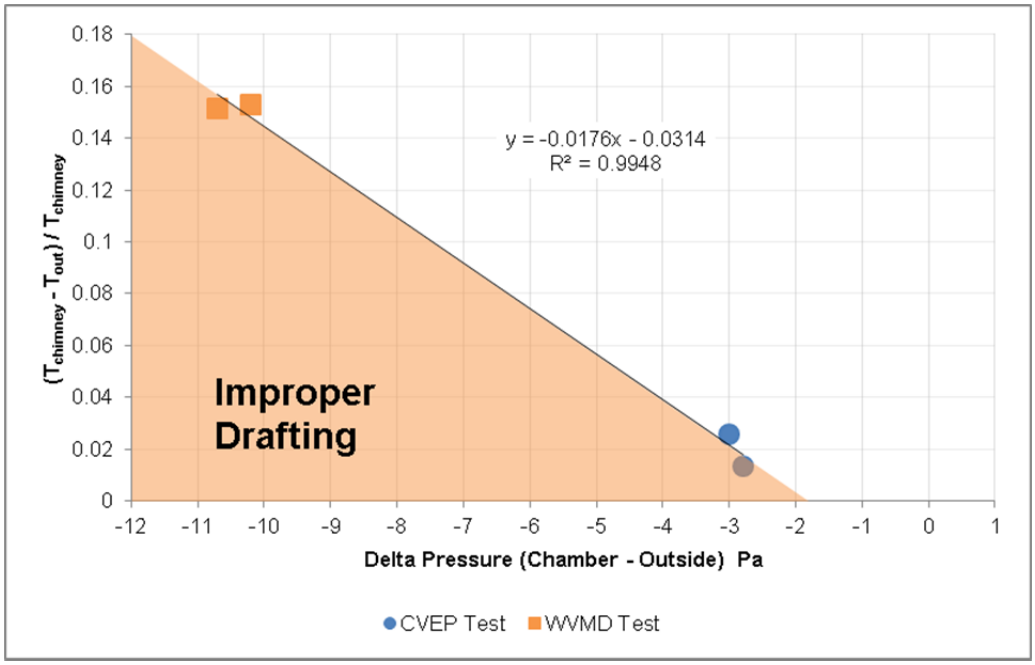


Fig. B.11. CVEP and WVMD for M&G DuraVent B Vent reline solution (see Fig. 1) water heater–only operation on the Type B metal chimney.

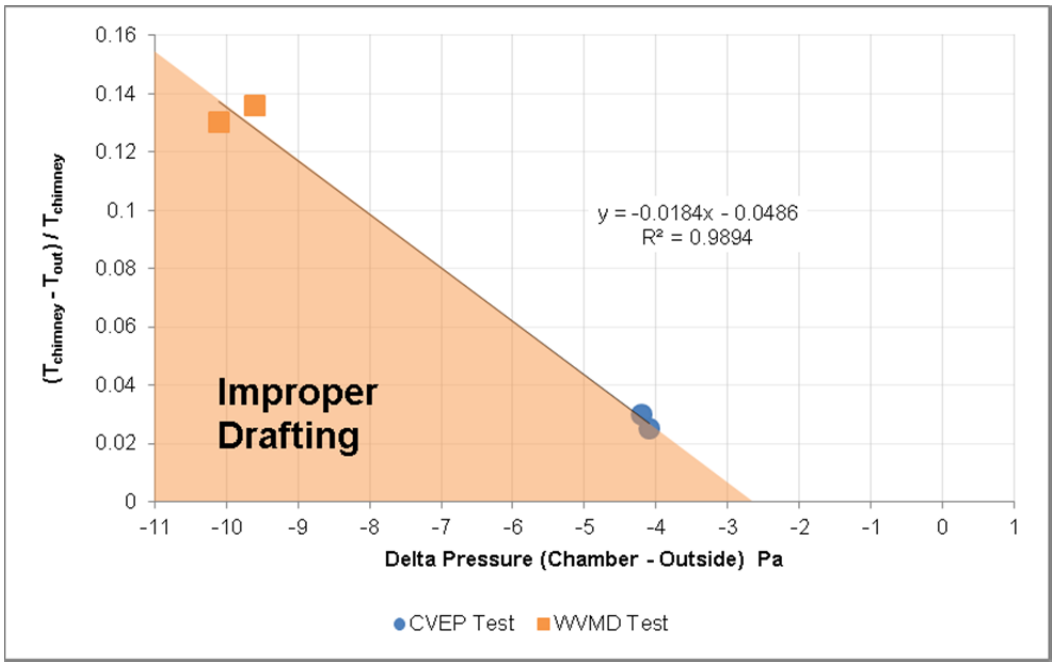


Fig. B.12. CVEP and WVMD for M&G DuraVent B Vent reline solution (see Fig. 1) water heater and noncondensing furnace operation on the Type B metal chimney.

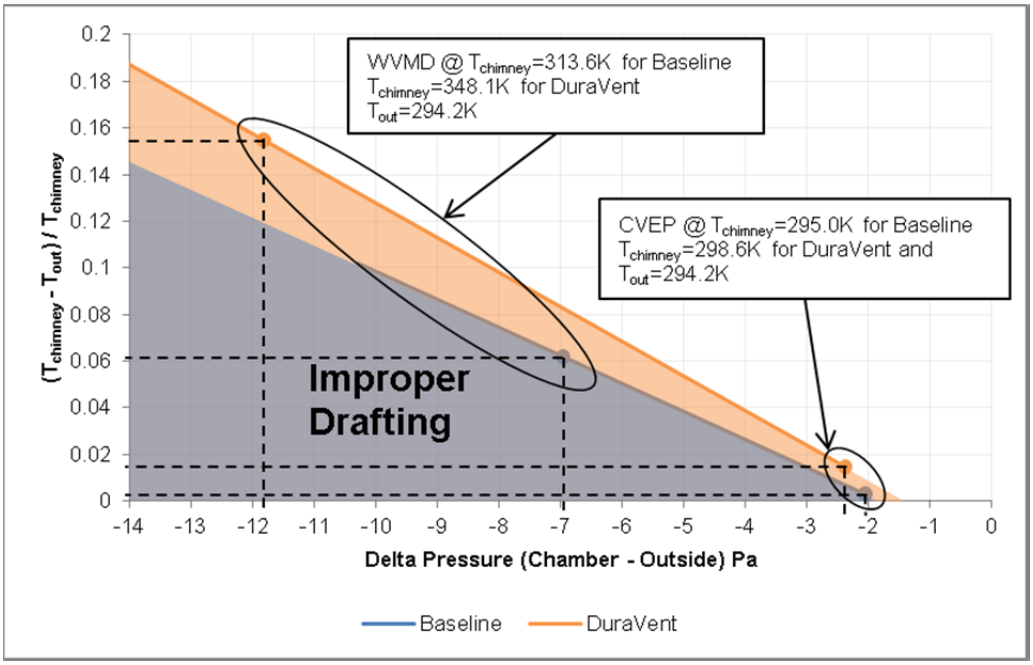


Fig. B.13. Determination of CVEP and WVMD from baseline and M&G DuraVent dual-flex reline solution [see Fig. 2(a)] water heater–only test data for the masonry chimney.

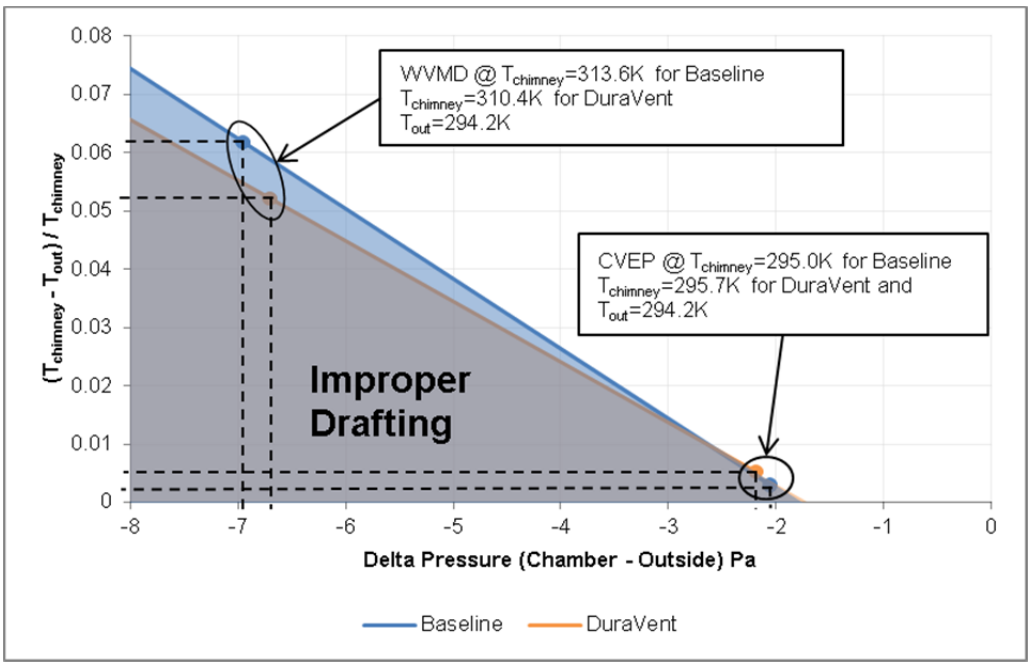


Fig. B.14. Determination of CVEP and WVMD from baseline and M&G DuraVent single-flex reline solution [see Fig. 2(b)] water heater–only test data for the masonry chimney.

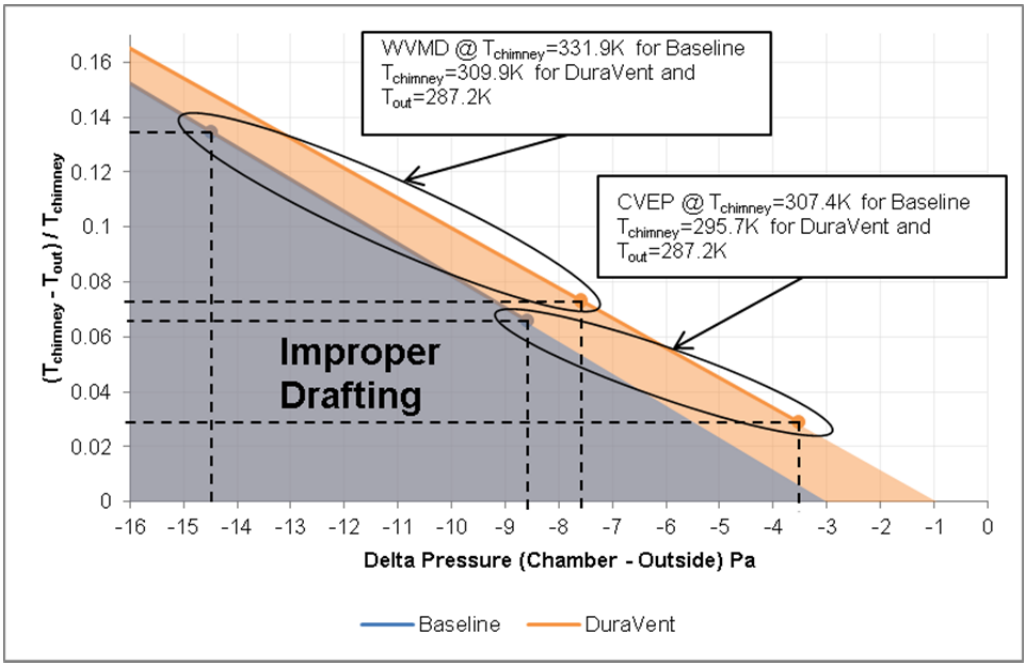


Fig. B.15. Determination of CVEP and WVMD from baseline and M&G DuraVent single-flex reline solution [see Fig. 2(b)] water heater and condensing furnace test data for the masonry chimney.

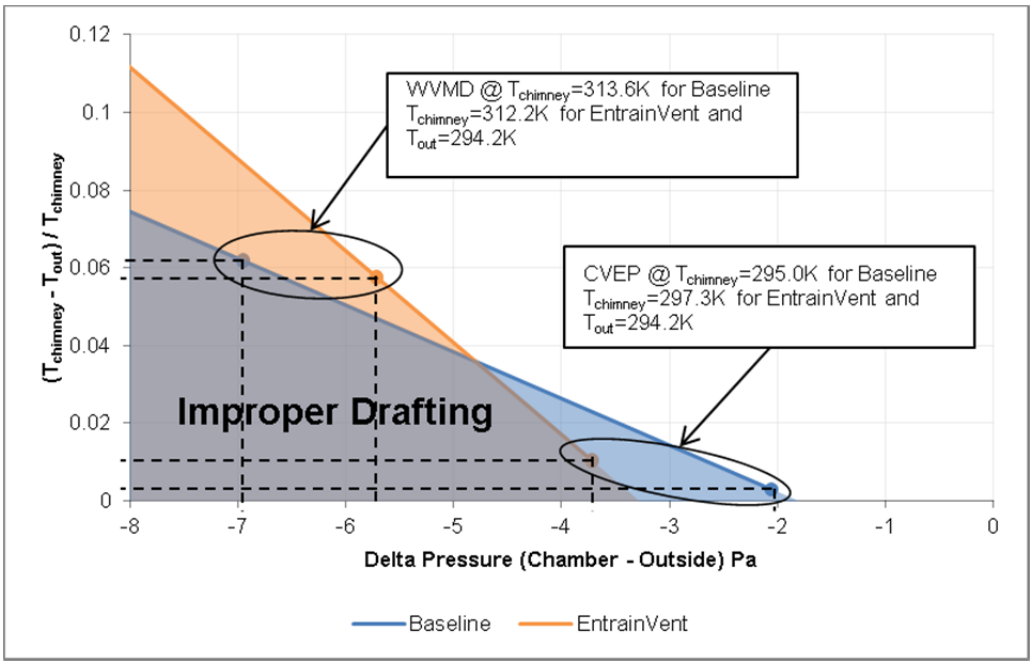


Fig. B.16. Determination of CVEP and WVMD from baseline and EntrainVent single-reline solution (see Fig. 5) water heater–only test data for the masonry chimney.

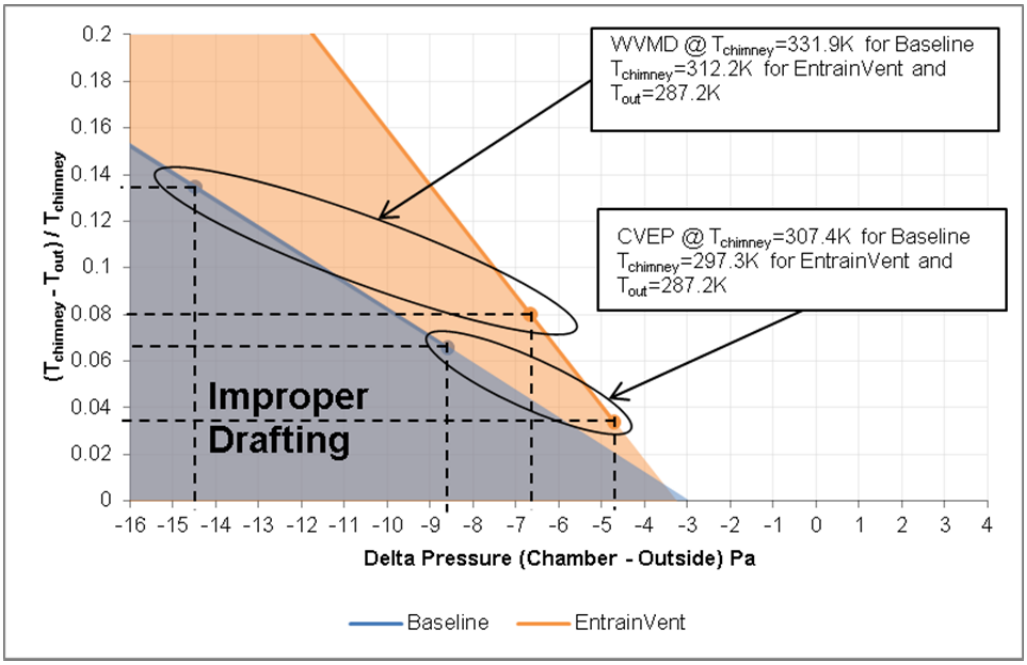


Fig. B.17. Determination of CVEP and WVMD from baseline and EntrainVent single-reline solution (see Fig. 5) water heater and condensing furnace test data for the masonry chimney.

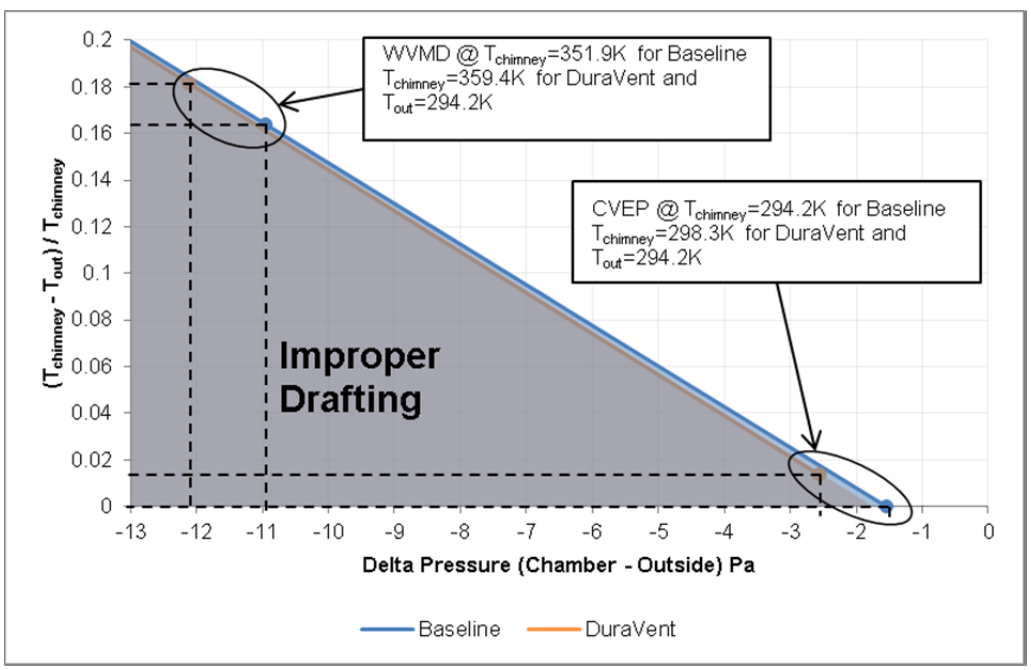


Fig. B.18. Determination of CVEP and WVMD from baseline and M&G DuraVent B Vent reline solution (see Fig. 1) water heater–only test data for the Type B metal chimney.

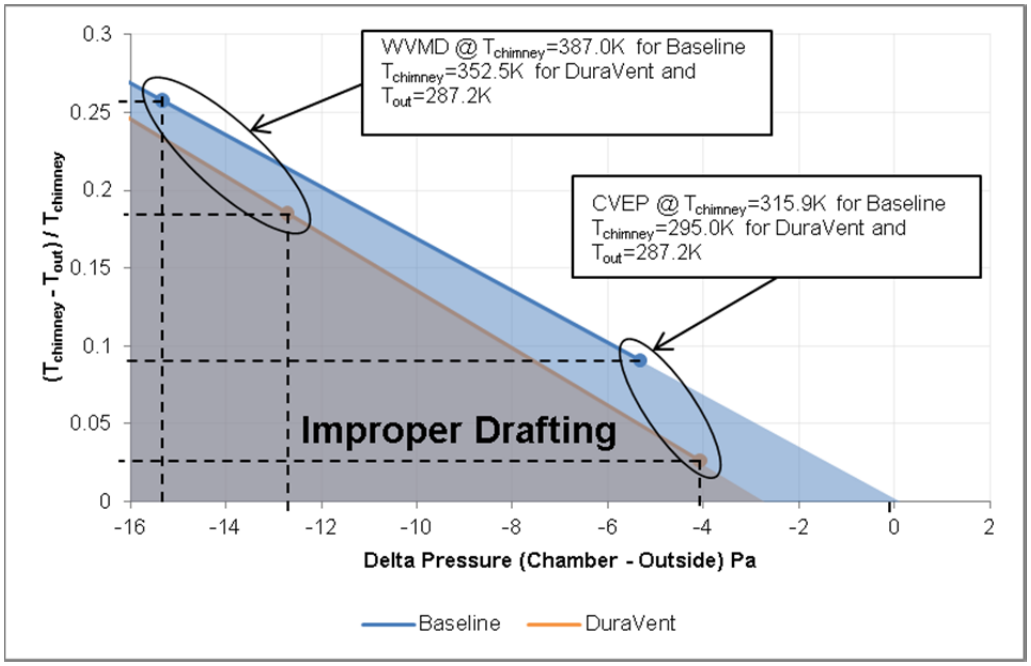


Fig. B.19. Determination of CVEP and WVMD from baseline and M&G DuraVent B Vent reline solution (see Fig. 1) water heater and condensing furnace test data for the Type B metal chimney.

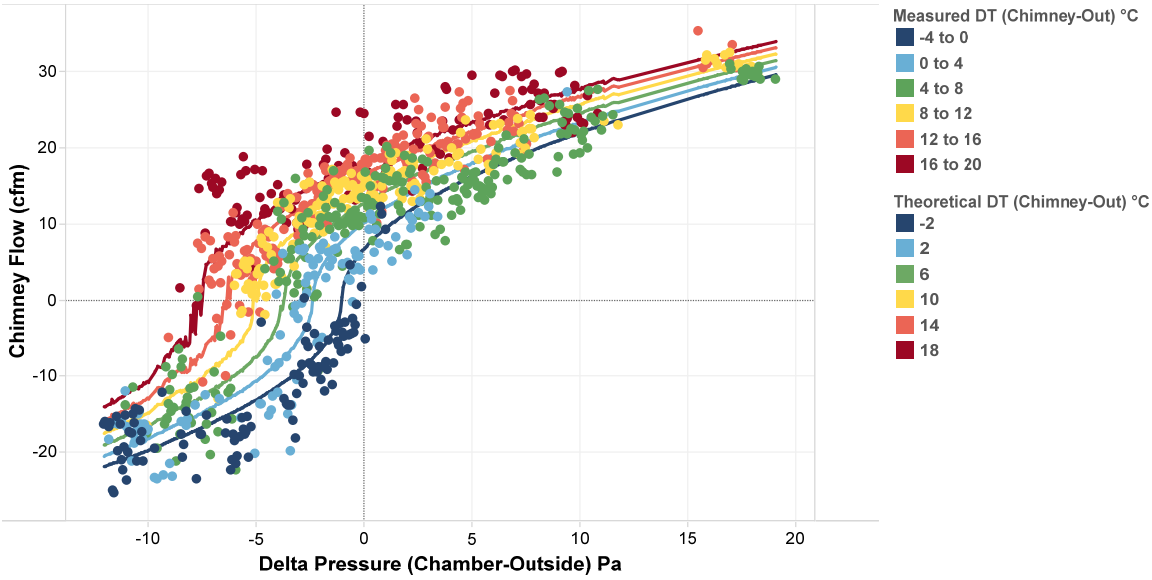


Fig. B.20. Experimental and theoretical total chimney flow for baseline water heater–only operation on the masonry chimney.

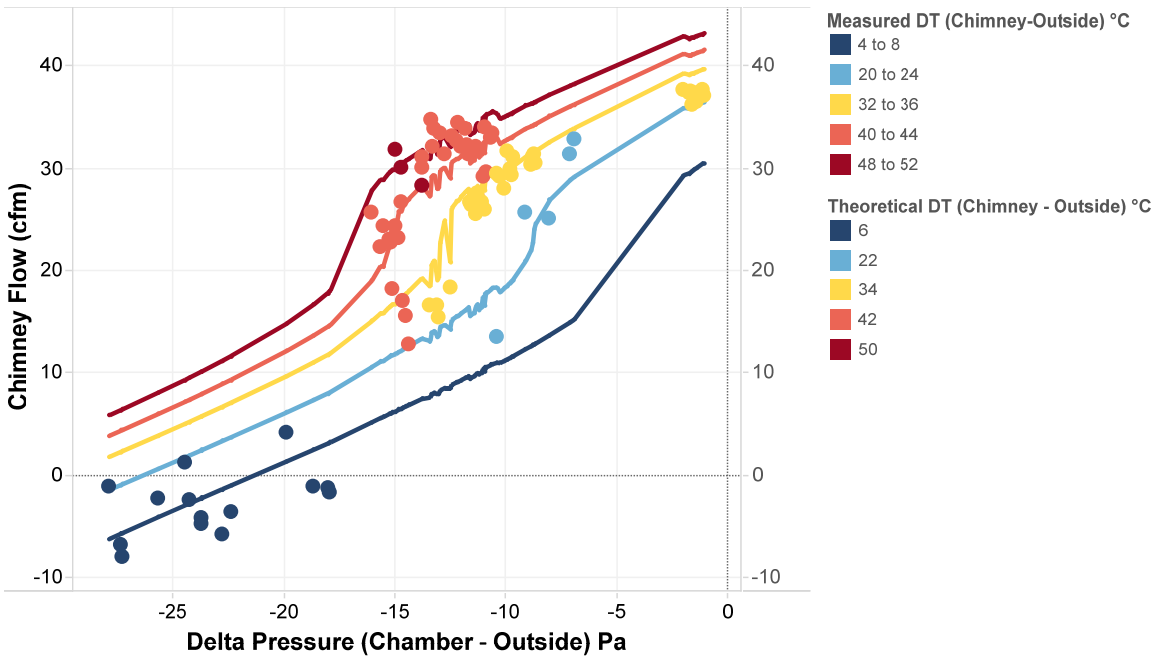


Fig. B.21. Experimental and theoretical total chimney flow for baseline water heater and noncondensing furnace operation on the masonry chimney.

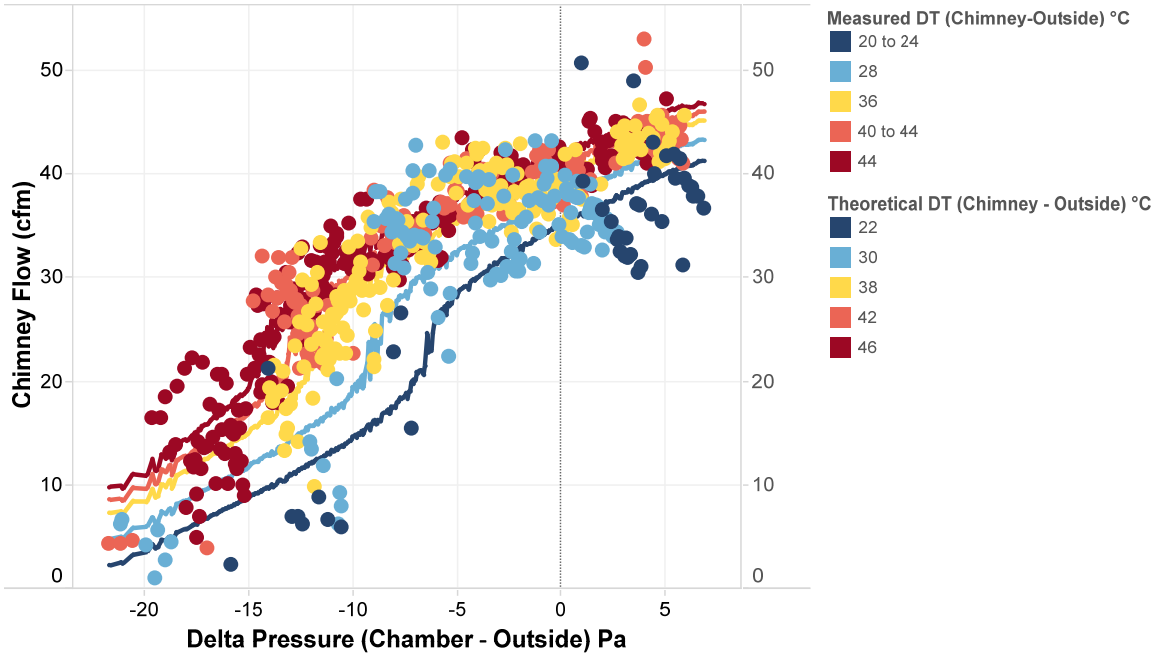


Fig. B.22. Experimental and theoretical total chimney flow for baseline noncondensing furnace–only operation on the masonry chimney.

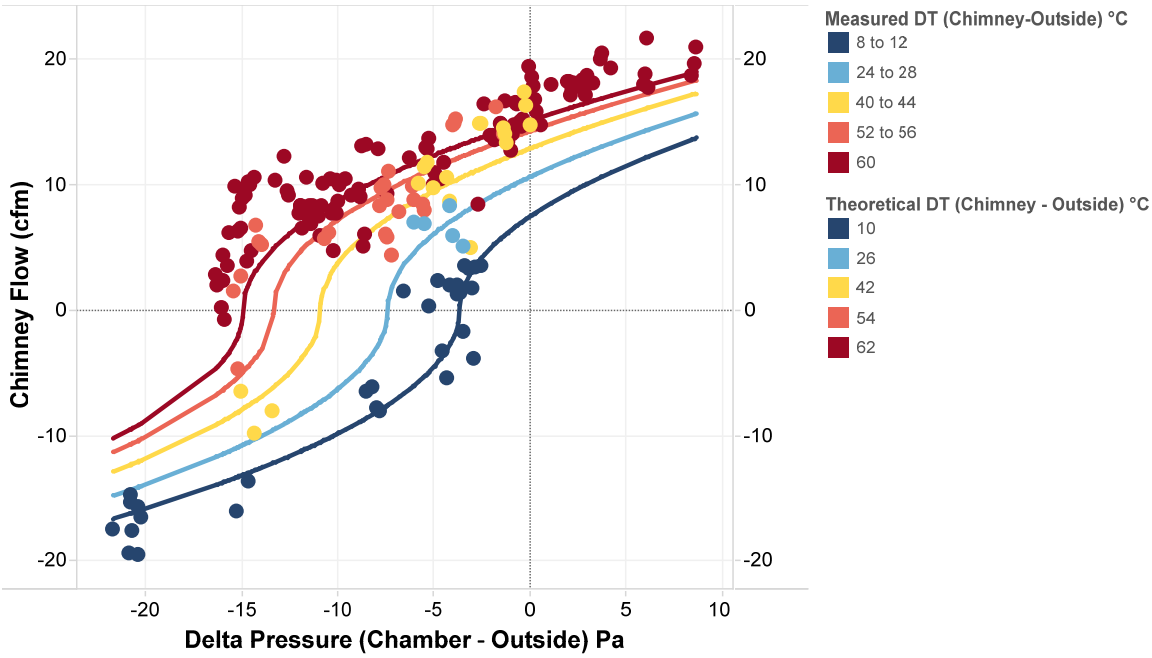


Fig. B.23. Experimental and theoretical total chimney flow for M&G DuraVent dual-flex reline solution water heater–only operation on the masonry chimney.

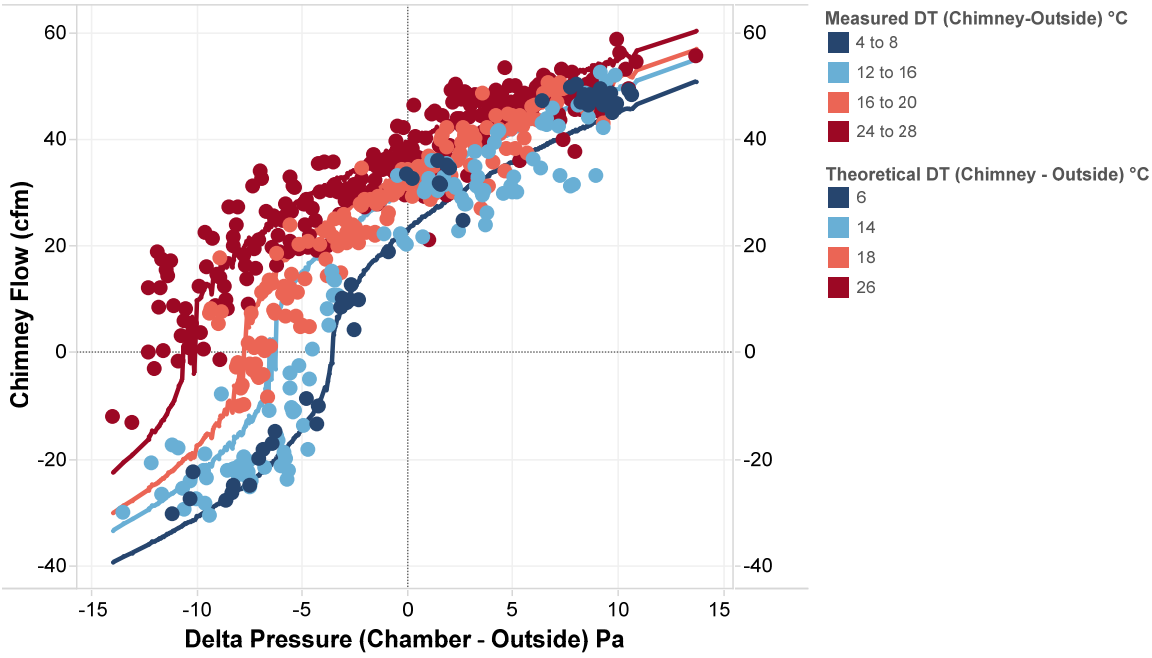


Fig. B.24. Experimental and theoretical total chimney flow for M&G DuraVent single-flex reline solution water heater–only operation on the masonry chimney.

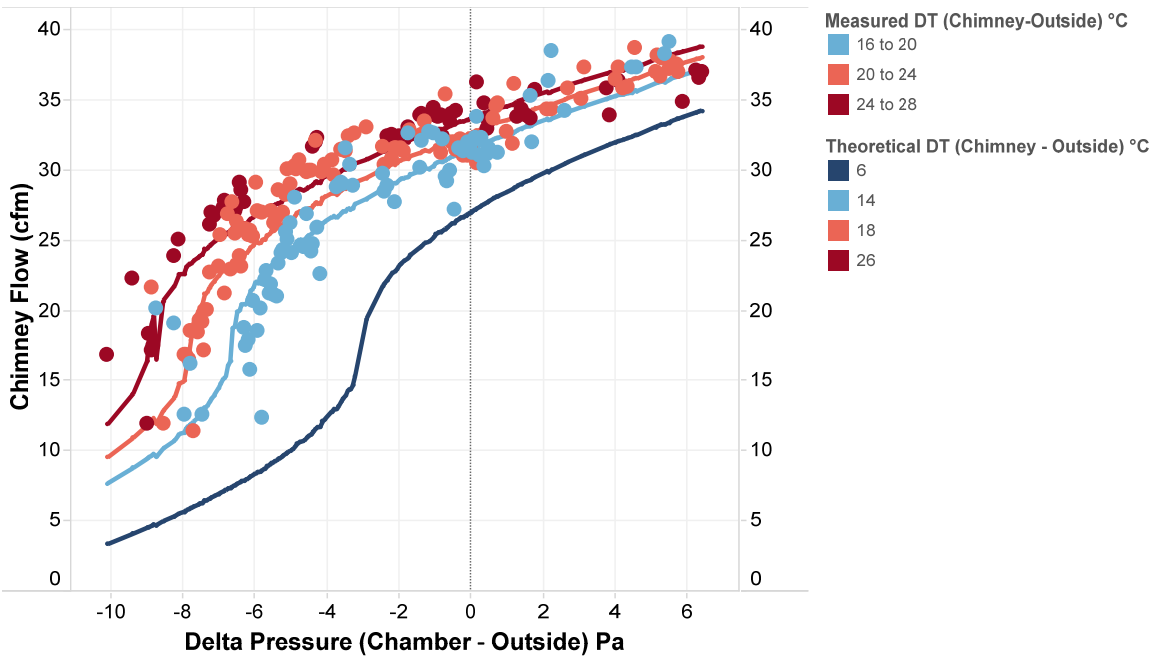


Fig. B.25. Experimental and theoretical total chimney flow for M&G DuraVent single-flex reline solution water heater and condensing furnace operation on the masonry chimney.

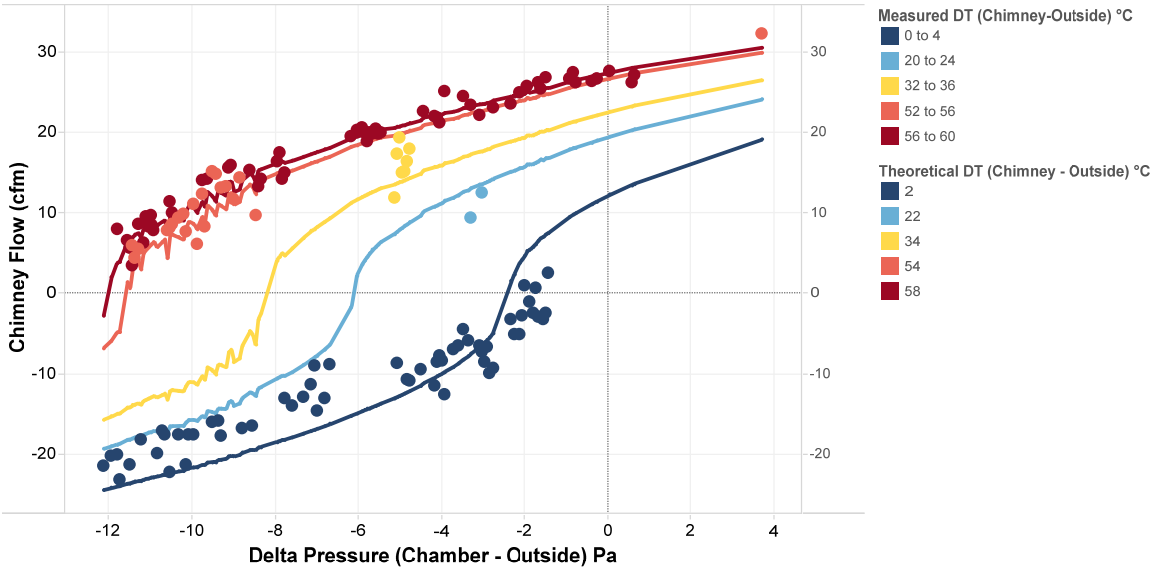


Fig. B.26. Experimental and theoretical total chimney flow for baseline water heater–only operation on the Type B metal chimney.

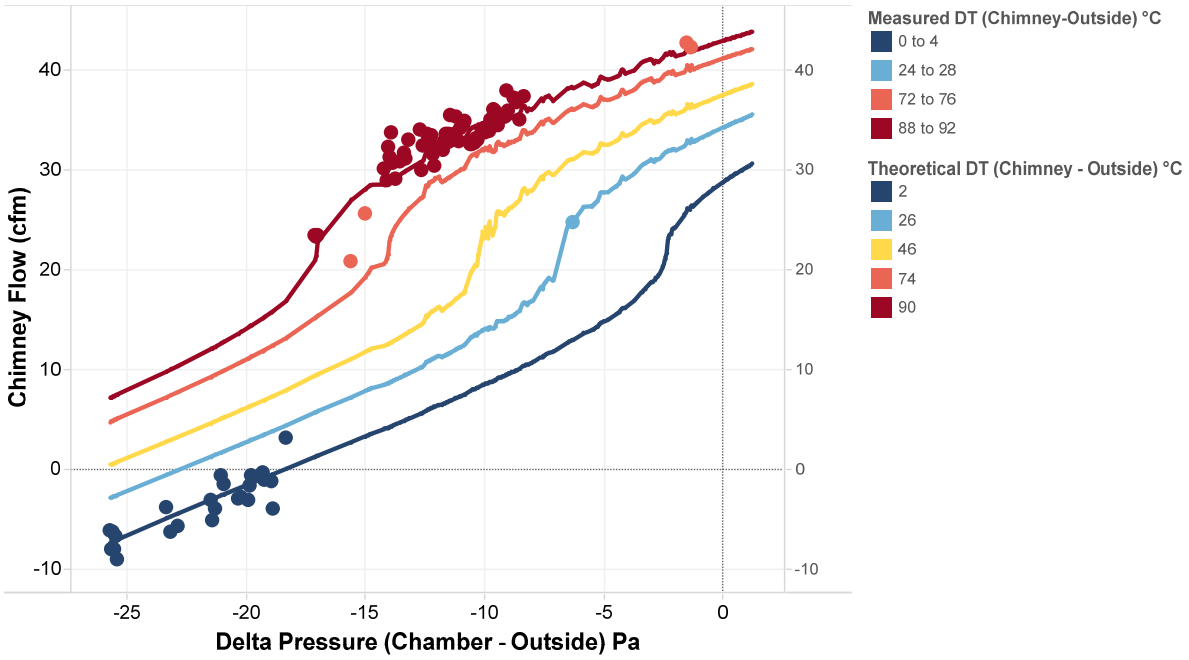


Fig. B.27. Experimental and theoretical total chimney flow for baseline water heater and noncondensing furnace operation on the Type B metal chimney.

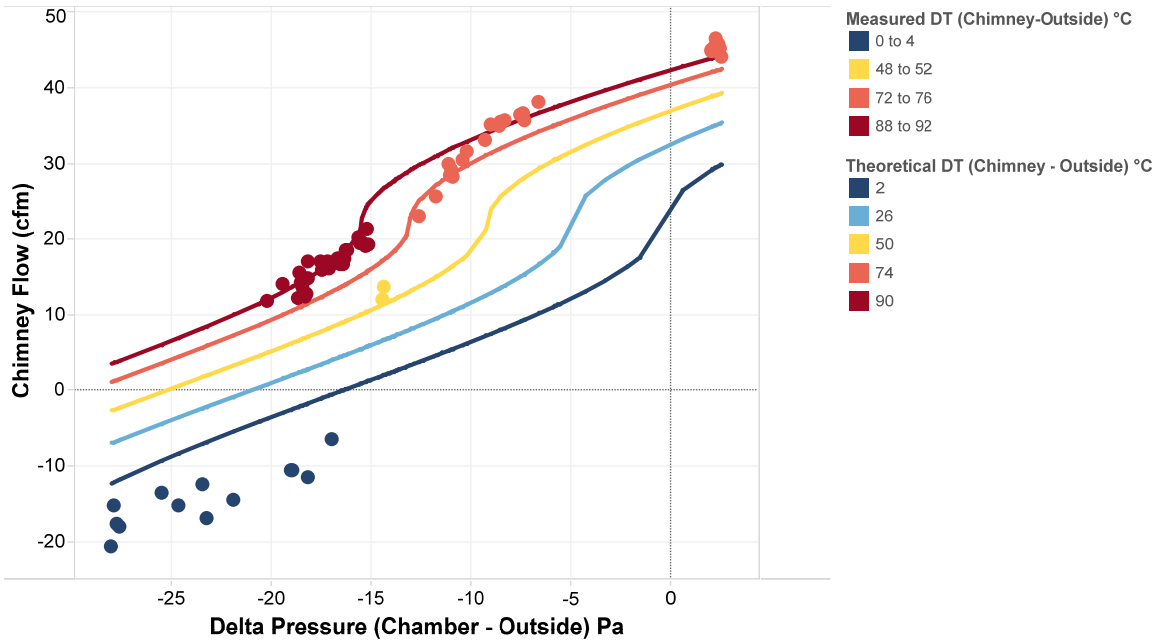


Fig. B.28. Experimental and theoretical total chimney flow for baseline noncondensing furnace–only operation on the Type B metal chimney.

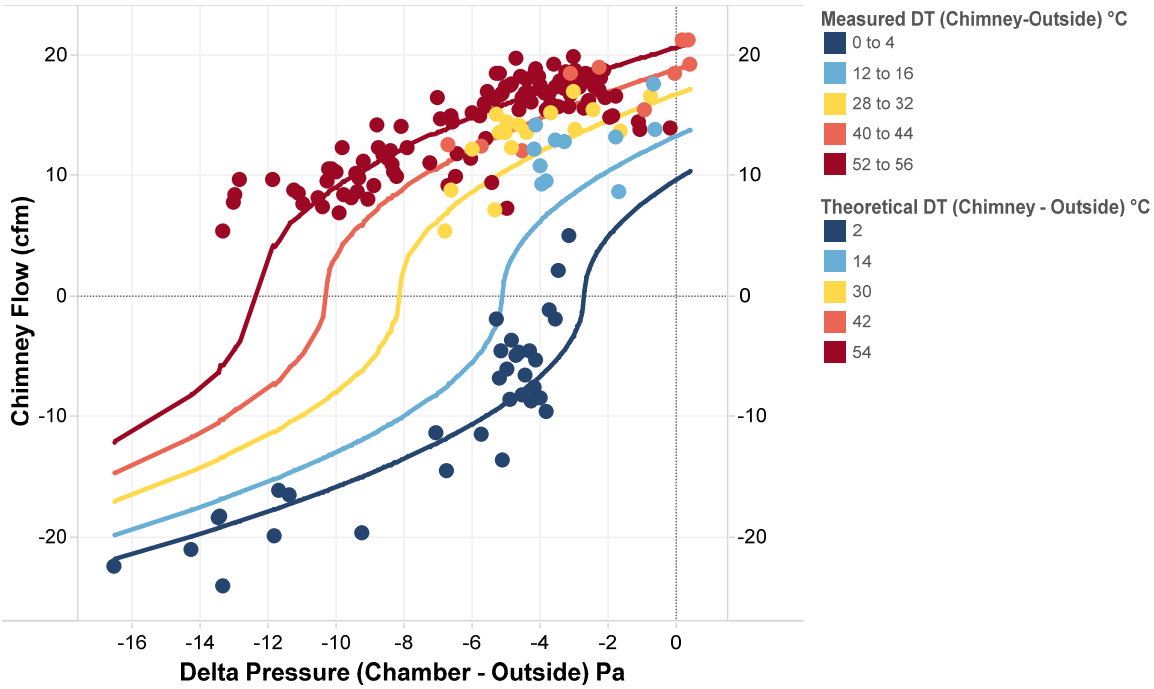


Fig. B.29. Experimental and theoretical total chimney flow for M&G DuraVent B Vent reline solution water heater–only operation on the Type B metal chimney.

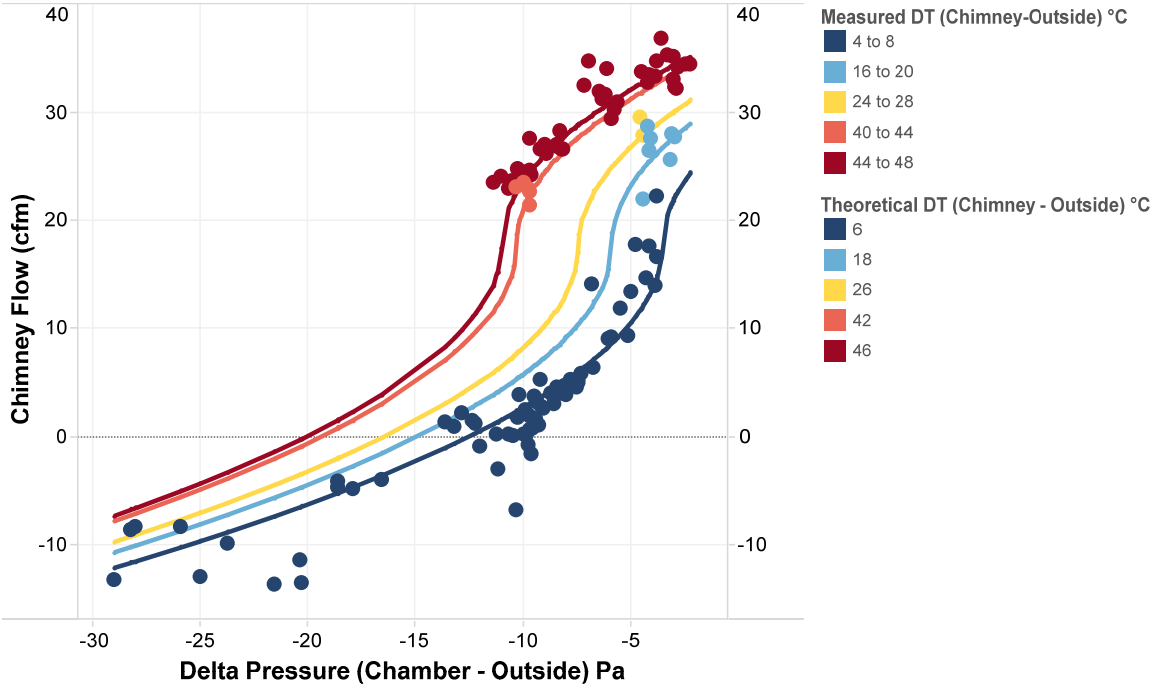


Fig. B.30. Experimental and theoretical total chimney flow for M&G DuraVent B Vent reline solution water heater and condensing furnace operation on the Type B metal chimney.

APPENDIX C: APPLIANCE, CHIMNEY, VENT CONNECTOR, AND SOLUTION SPECIFICATIONS

Table C.1. Appliance specifications

Appliance type	Model #	Rated input (Btu/h)	Rated AFUE (%) or EF
Natural draft water heater	GG40T06AVG01	36,000	0.59
Noncondensing furnace	GMS80804BN	80,000	80%
Condensing furnace	GKS90703BX	69,000	92.1%

Table C.2. Test configurations

Configuration under test	Appliance	Chase for liners (if applicable)	Vent Connecting Appliance To Chimney				Chimney		
			Material	Connector diameter (in)	Connecter rise[a] (ft)	Connector run (ft)	Material	Diameter (in) or flow area (in^2)	Vent height[b] (ft)
Baseline masonry	Water heater	NA	Type B metal vent	3	1.8	5	Clay tile–lined masonry	77 in^2	25.5
	Noncondensing furnace	NA	Type B metal vent	4	2.4	7.5			
Baseline Type B vent	Water heater	NA	Type B metal vent	3	1.8	10.3	Type B metal vent	5 in	22.3
	Noncondensing furnace	NA	Type B metal vent	4	2.4	8.8			
M&G DuraVent single-flex reline masonry chimney	Water heater	NA	Type B metal vent	3	NA	5	Clay tile–lined masonry	74 in^2	25.5
	Condensing furnace	Clay tile–lined masonry	PolyPro® (rigid polypropylene)	2	NA	7	FasNSeal® (flexible AL29-4C®)	2 in	25.3
M&G DuraVent dual-flex reline masonry chimney	Water heater	Clay tile–lined masonry	Type B metal vent	3	NA	5	DuraFlex aluminum	3 in	25.5
	Condensing furnace	Clay tile–lined masonry	PolyPro® (rigid polypropylene)	2	NA	7	FasNSeal® (flexible AL29-4C®)	3 in	25.3
M&G DuraVent B Vent reline	Water heater	NA	Type B metal vent	3	NA	10.3	Type B metal vent	16.1 in^2	22.3
	Condensing furnace	Type B metal vent	PolyPro® (rigid polypropylene)	2	NA	8.8	FasNSeal® (flexible AL29-4C)	2 in	22.1
Fan-assisted water heater dual-reline	Water heater	Clay tile–lined masonry	Type B metal vent	3	NA	5	Stainless steel flex	2 in	25.5
	Condensing furnace	Clay tile–lined masonry	PolyPro® (rigid polypropylene)	2	NA	7	FasNSeal® (flexible AL29-4C®)	2 in	25.3
EntrainVent single-reline	Water heater	NA	Type B metal vent	3	NA	5	Clay tile–lined masonry	70 in^2	25.5
	Condensing furnace	Clay tile–lined masonry	PolyPro® (rigid polypropylene)	2	NA	7	FasNSeal® (flexible AL29-4C®)	3 in	25.3

[a]As defined by NFPA 54 13.2.12.
[b]As defined by NPFA 54 13.2.13 for common-vented appliances.