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Heat Pump Water Heater Using Wrapped-Tank Microchannel Condenser Coil for Charge Reduction – FY19 1st Quarter (Regular) Milestone Report: Development of Wrapped-Tank Condenser Model (Round Tube and Microchannel), Coupled with Water Tank Model

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Development of Wrapped-Tank Condenser Model (Round Tube and Microchannel), Coupled with Water Tank Model
(Regular Milestone)

Executive Summary

We recentally growed the DOE/HPDM model library to enhance its heat pump water heater (HPWH) design and simulation capability. The new addtions include wrapped-tank round tube coil, microchannel coil and a one-dimensional stratified water tank. A wrapped-tank condenser coil has strong coupling with a stratified water tank, which leads HPWH simulation a transient process. The new one-dimensional stratified water tank model is an improvement to the open-source EnergyPlus water tank model, by introducing a calibration factor to account for bulk mixing effect due to water draws and circulations, etc. The wrapped-tank condenser coil model, using a segment-to-segment modeling approach to simulate round tubes or microchannel ports. The heat exchanger models can accept aribitrary refrigerant types, e.g. HFCs, HFOs, natural refrigerants like CO_2 and propane, etc.

Development of Stratified Water Tank Model:

EnergyPlus 1-Dimensional Water Tank Model:

EnergyPlus is an open-source, building energy simulation software developed by the U.S. Department of Energy and has both stratified and mixed water tank models. The EnergyPlus stratified water tank model is a one-dimensional model, simulating water temperature stratification up to 10 nodes. Each node is a control volume, having uniform temperature and water property values. It uses Euler forward difference method for time dependent functions. The temperature change in each node is solved as Equation 1,

$$m_n \times Cv \times \frac{dT_n}{dt} = q_{net,n} \qquad (1)$$

Where:

n represents the node index. m_n is the node water mass, Cv is the water specific heat at constant volume, T_n is the node water temperature, t is the time step, and $q_{net,n}$ is the net heat transfer rate to the node.

The net node heat transfer rate is calculated using Equation 2,

$$q_{net,n} = q_{heater,n} + q_{oncycpara,n} + q_{offcycpara,n} + q_{oncycloss,n} + q_{offcycloss,n} + q_{cond,n} + q_{use,n} + q_{source,n} + q_{flow,n} + q_{invmix,n} \qquad (2)$$

Where:

$q_{heater,n}$ is the auxiliary heater capacity in the node. The tank model can simulate two separate auxiliary heaters, usually one at the top of the tank and the other at the bottom. The heaters can be turned on or off, determined by each heater's set point and dead band. $q_{oncycpara,n}$ and $q_{offcycpara,n}$ are parasitic loads added when a heating cycle is on and off. $q_{oncycloss,n}$, $q_{offcycloss,n}$ are heat losses when a heating cycle is on and off. The two heat losses are heat dissipated from the node to the surrounding air. They are determined by surface loss coefficients, i.e. insulation levels. $q_{cond,n}$ is the conduction heat between two neighboring nodes. $q_{use,n}$ is the heat transfer rate to or from a use side connection. $q_{source,n}$ is the heat transfer to or from a source side connection, for example, heat added by a heat pump. If the water tank is coupled with a wrapped-tank coil, $q_{source,n}$ is calculated using a pre-defined fraction of the condenser heat. $q_{flow,n}$ is the energy transfer rate caused by water flowing in and out of the node. $q_{invmix,n}$ is the inversion mixing rate caused by natural convection upward flow driven by the temperature difference between two neighboring nodes. It is defined in Equation 3,

$$q_{invmix,n} = \dot{m}_{inmix,n+1} \times Cp \times (T_{n+1} - T_n) + \dot{m}_{inmix,n-1} \times Cp \times (T_{n-1} - T_n) \quad (3)$$

Where:

$\dot{m}_{inmix,n+1}$ and $\dot{m}_{inmix,n-1}$ are mass flow rates from upper and lower nodes to the node, due to temperature inversion mixing. Clearly, the mixing is driven by the water temperature and density difference. The inversion mixing flow rate is defined in Equation 4,

$$\dot{m}_{inmix,n} = 0.5 \times m_n/dt \quad (4)$$

Where:

dt is the time step. 0.5 is an empirical parameter, hard-coded in the EnergyPlus model.

The EnergyPlus stratified water tank model is open source and most widely used. It was verified to be adequately accurate in simulating nodal tank shell losses, placements of electric heater elements, thermostats, etc. It models water piston flow, i.e. bulk water flow from a make-up port to a supply port, heat conduction between water nodes and natural convection up-flow and mixing. However, a missing mechanism was identified via this study, for which an improved modeling approach is presented in this paper.

Improved Stratified Water Tank Model:

To validate the EnergyPlus stratified water tank model, the tank node temperature profile measured by Murphy et al. (2011) was used for comparison. It was observed that the EnergyPlus tank model tends to over-estimate the water temperature stratification, i.e. the predicted temperature difference between the top and bottom was larger than the measured value, especially when there is a big water draw. It was speculated that the tank model failed to account for bulk mixing during big water draws. Large bulk water flows (typical of large hot water draw events like showers, etc.) cause whirls leading to bulk mixing effects between tank nodes. To reveal the impact of this effect, a CFD study was performed to simulate the water tank used in Murphy et al. (2011), shown in Figure 1. The tank supply node was at the top and the make-up node at the bottom, with cold make-up water supplied via a dip tube. Figure 1 depicts traces of the localized water flow at a 3 GPM (0.001136 m^3/minute) water draw rate. Two apparent backflow whirls can be seen at the lower half of the tank. The backflow effect leads to bulk mixing and reduces the level of water temperature stratification. This mechanism is not accounted for in the EnergyPlus tank model.

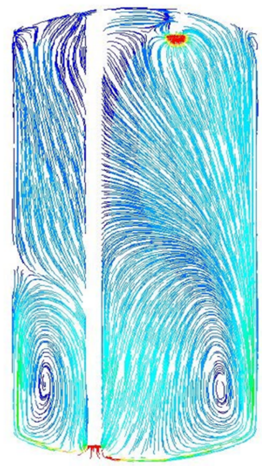

Figure 1: CFD simulation of water tank (Elatar, 2017) having a 3 GPM water draw

A CFD tank model can more accurately represent the physics of the tank mixing phenomena, etc.; however, it is too slow for HPWH energy simulations. A 1-D stratified tank model is fast enough, but it can't describe mixing mechanisms due to two-dimensional or three-dimensional flow. It is necessary to bridge the simplified tank model with a detailed CFD model or experimental measurements. Thus, an empirical bulk mixing term, a calibration factor, is introduced to adjust the simplified tank model. The calibration accounts for the energy transfer between the tank average and nodal temperatures caused by the whirls, as shown in Equation 5.

$$q_{bulkmix,n} = Ratio_{bulkmix} \times (T_{avg,tank} - T_n) \times m_n \times Cp \qquad (5)$$

where:

$Ratio_{bulkmix}$ (ratio of nodal water mass exchanging energy with the bulk flow) is an empirical factor to correlate the mixing effect, it can be derived by calibration against measured data or CFD simulation. $Ratio_{bulkmix}$ should be different values with/without water draw. $T_{avg,tank}$ is the tank average water temperature at each time step. $q_{bulkmix,n}$ is the energy transfer rate to each node, caused by the bulk mixing effect of the backflow whirls. If more detailed experimental or CFD simulation data are available, $Ratio_{bulkmix}$ can be derived specific to different regions of a water tank, for example, a bulk mixing ratio may be larger, if adjacent to a flow disturbance, i.e. the supply and return water ports; but smaller, if away from a flow disturbance. For this case, $T_{avg,tank}$ should be an average of the node temperatures in the region having the same bulk mixing ratio.

Using the measured data from Murphy et al. (2011), the figures below compare the measured water temperature stratification from the top node to the bottom mode, with the model predictions. Figure 2 shows the comparison to the un-calibrated model and Figure 3 shows the comparison to the calibrated model. The calibrated model was adjusted using 0.15% tank water bulk mixing ratio during 3 GPM (0.001136 m^3/minute) water draw, and zero bulk mixing when no draw. It can be seen that the calibrated model matches the measured water profile closely, with a reasonable calibration factor. In the two figures, the biggest temperature differences between the top and bottom are at the start of the 3 GPM (0.001136 m^3/minute) water draws.

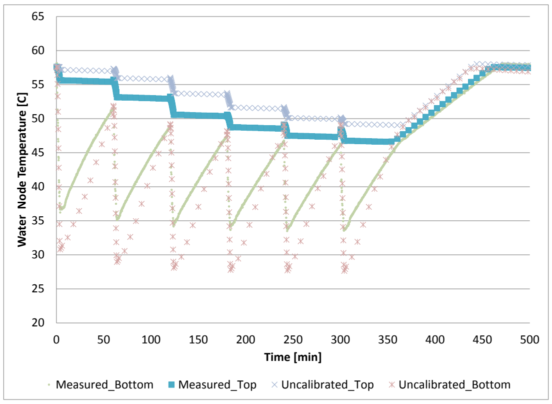

Figure 2: Compare water stratifications of measured and predicted by the uncalibrated 1-D tank model

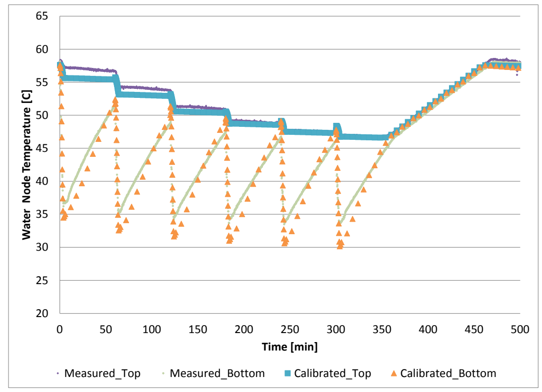

Figure 3: Compare water stratifications of measured and predicted by the calibrated 1-D tank model

Development of Wrapped-Tank Condenser Coil:

<u>Segment-to-Segment Wrapped Tank Condenser Model:</u>

The EnergyPlus tank model can work with wrapped-tank coils but requires inputting constant condenser heat fractions (fractions of total condenser capacity) to nodes using the condenser capacity from a HPWH performance curve. This is an over-simplification, because in reality the condenser coil heat transfer is strongly coupled with the tank temperature distribution and is never constant in the heating cycle. The coil configuration impacts the tank water stratification and the water temperature profile is the boundary condition to the condenser coil heat transfers.

To reveal the interaction between a stratified water tank and the wrapped-tank coil, a new wrapped-tank condenser model was developed, using a segment-to-segment modeling approach. Each single condenser coil tube or microchannel port is divided to numerous segments, and each segment is allocated to its geometrical location on the tank. The heat transfer and pressure drop in each segment is calculated along the refrigerant flow direction. In the segment where phase change occurs, the phase transition point is determined. Figure 4 illustrates the overall heat transfer of one segment. It comprises the refrigerant side condensing heat transfer, the conductive resistance due to the tube or port and tank wall thickness, and the natural convective heat transfer between the water node and tank wall. The heat transfer is driven by the difference between the average refrigerant temperature in the segment and the temperature of the water node where the tube segment is located. The arrows in Figure 4 indicate the refrigerant flow direction.

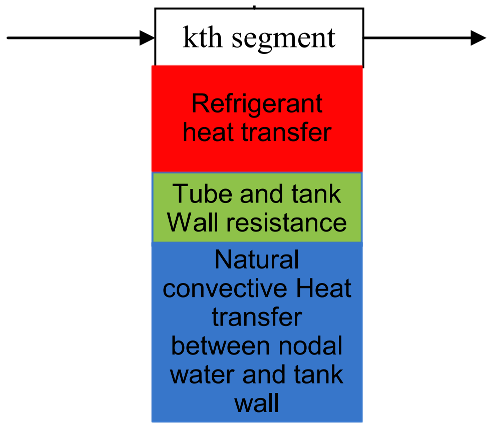

Figure 4: Overall Heat Transfer between a Tube segment in a Wrapped-Tank Coil and a Water Node

At the refrigerant side, the flow-pattern-dependent heat transfer correlation published by Thome (2003) was used to calculate the condenser two-phase heat transfer coefficient. The single-phase heat transfer was calculated using the Dittus-Boelter correlation (Dittus and Boelter 1930). The two-phase pressure drop was modeled using the correlation published by Kedzierski (1999), and the single-phase pressure drop was modeled as fully-developed turbulent internal flow in a smooth tube, as described in the Moody diagram (Moody, 1944). A non-circular tube is approximated as a round tube by inputting the hydraulic diameter. The contact surface area between the refrigerant tube and the tank wall is a user input, as this is subject to using thermal adhesive or not. The natural convective heat transfer between the water and the tank wall is simulated by Churchill and Chu (1975), assuming natural convective heat transfer from a vertical plate.

Figure 5 describes the information flow between the water tank and the wrapped-condenser coil models in one quasi-steady-state simulation step. The dashed lines indicate separations of the tube segments.

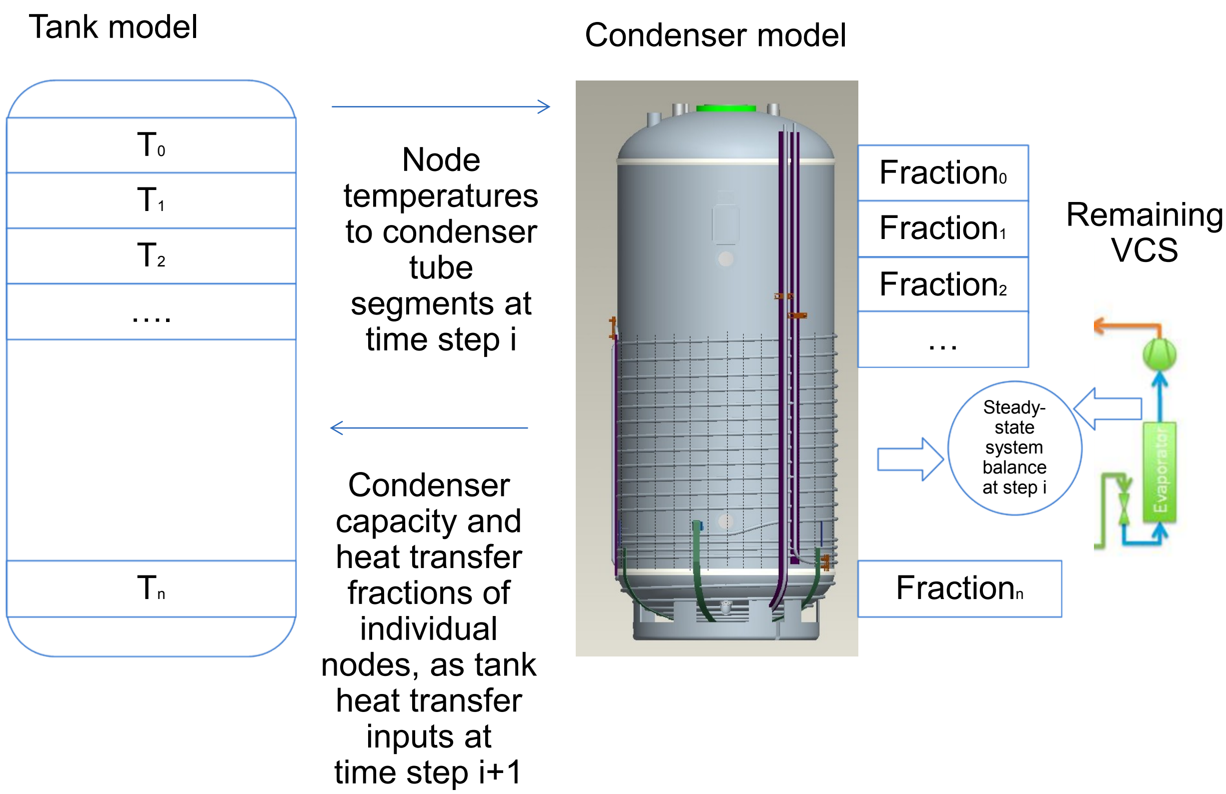

Figure 5: Information Flow between Tank, Wrapped-Tank Coil and Heat Pump System in One Time Step. At the beginning of one time step, the water node temperatures are treated as boundary conditions to drive the heat transfer in individual tube segments associated with the tank nodes via geometrical locations. The condenser model balances with the other components in the VC cycle model to calculate steady-state system balance points at one moment. As a result, the condenser capacity is determined and the heat transfer fractions are distributed to individual nodes by accumulating the heat transfer rates of tube segments in each node. At the end of the time step, the new water node temperatures are calculated based on the condenser heat fractions. Then, the updated node temperatures become new boundary conditions to the condenser coil for the next time step. It should be noted, for a tank node having no condenser tubes at the location, the condenser heat fraction is zero. If multiple tubes are wrapped on the same tank node, the nodal temperature to the tubes is assumed the same.

References

Churchill, S.W., and Chu, H.H.S., 1975. "Correlating Equations for Laminar and Turbulent Free Convection from a Vertical Plate," International Journal of Heat and Mass Transfer, 18, 1323, 1975.

Dittus. F. W., and L. M. L. Boellter, 1930. University of California, Berkeley, Publications on Engineering, Vol. 2, p 443

Elatar, A. F., Nawaz K., Shen B., 2017, "Back Flow Characterization During Charging/Discharging of Wrap Coil Tank Model", ASME 2017 IMECE International Mechanical Engineering Congress & Exposition, 2017.

Kedzierski, M. A. and Choi J. Y., 1999, “A generalized pressure drop correlation for evaporation and condensation of alternative refrigerants in smooth and micro-fin tubes”, NISTIR 6333.

Moody, L. F., Trans ASME, 66, 671, 1944

Murphy, R. W., Baxter V. D., E. A. Vineyard, AND R. L. Linkous, 2011, “Drop-in evaluation of refrigerant r1234yf in a residential integral heat pump water heater,” Proceedings of the 10th International Energy Agency Heat Pump Conference.

Thome J. R., J. El Hajal and A. Cavallini, 2003, “Condensation in Horizontal Tubes, Part 2: New Heat Transfer Model Based on Flow Regimes”, International Journal of Heat and Mass Transfer, 46(18), Pages 3365-3387.