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Linked Modelling of Heat Pump Water Heater Vapor Compression System and Water Tank

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ABSTRACT

Heat pump water heaters (HWPHs) in the U.S. market are commonly designed as “drop-in” replacements for conventional water heating systems involving a close integration of the vapor compression system and the water storage tank. The design of interest is this study is the wrap-around condenser HPWH. The dynamic interdependence between the vapor compression system and the water in the storage tank poses a modelling challenge for steady-state refrigeration system models. The aim of this project is to a model and methodology for coupling steady-state vapor compression system modelling with a dynamic condenser cooling medium.

Consequently, a steady-state vapor compression system model is developed in Engineering Equation Solver (EES), and a computational fluid dynamics (CFD) model is developed in ANSYS Fluent for simulating the heat transfer and fluid dynamics in the water tank. The linked modelling process involves iteration between the CFD model of the water tank and the vapor compression system model in describing quasi-steady warm up of a heat pump water heating system. The models are connected at the interface of the tank wall and the water in the storage tank. Experimental validation of this modelling is underway.

As overall system performance is influenced by profiles of water temperature and velocity in the tank and refrigerant in the condenser, a wholesome understanding of heat distribution and fluid dynamics in the water tank can enable future design evaluations of various condenser coil architectures, component sizings, and refrigerants.

1. INTRODUCTION

1.1 Background and Objectives

Heat pump water heaters (HPWHs) offer more than twice the energy-efficiency of conventional electric and gas water heaters, and have been in the U.S. market for more than twenty years. As of today, several manufacturers produce HPWHs. This study is based on wrap-around condenser, air-source, “integrated,” HPWHs designed as a drop-in replacement to conventional water heaters. By integrating the vapor compression system with the water storage tank, the unit is made to have the same footprint and form factor to adapt to the design of traditional homes. One means of achieving this is by wrapping the water storage tank with a coil condenser.

Fardoun et al. (2011) developed a transient quasi-stady model of an air-source HPWH with a water tank external to the vapor compression system. In this case, lumped parameter modelling was utilized and the modelling of heat transfer in the vapor compression system and water tank are simplified. A similar approach is utilized by Kim et al. (2003) in which stratification of temperature in the water tank is not considered. A challenge in applying this method of modelling to wrap-around coil condenser HPWHs is the strong interdependence between the vapor compression system and the fluid dynamics and thermal behavior of the water in the storage tank as the heat transfer between each condenser coil and the volume of water local to that coil is governed by local fluid states and flow characteristics.

The objectives of this study are to develop a model the captures the transient behavior in the water tank in addition to the dynamic progression of the overall vapor compression system. The goal of this modelling method is understand heat transfer in the condenser on a coil by coil level in addition to a macro, component level. A well-developed model can then be used in future work to assess the merits of the condenser design and reveal specific insights by relating geometric and system level design parameters to system performance in terms of COP, capacity, and warm-up time.

1.2 System Description and Experimental Facility

The modelling and simulation work is currently centered about a hybrid electric, air-source heat pump water heater with a wrap-around coil condenser. A schematic of the instrumented R134a vapor compression heat pump system is shown in Figure 1. The system is an air-source heat pump with a copper coil condenser that wraps around the walls of the stainless steel water tank of 80 gallon capacity. The original design for this particular system also relies on immersed electric resistance heaters that operate in lieu of the heat pump system when demand or temperature difference exceeds the ability of the heat pump to supply hot water adequately. For this project, the electric heaters have been removed from the original system to study solely the vapor compression system.

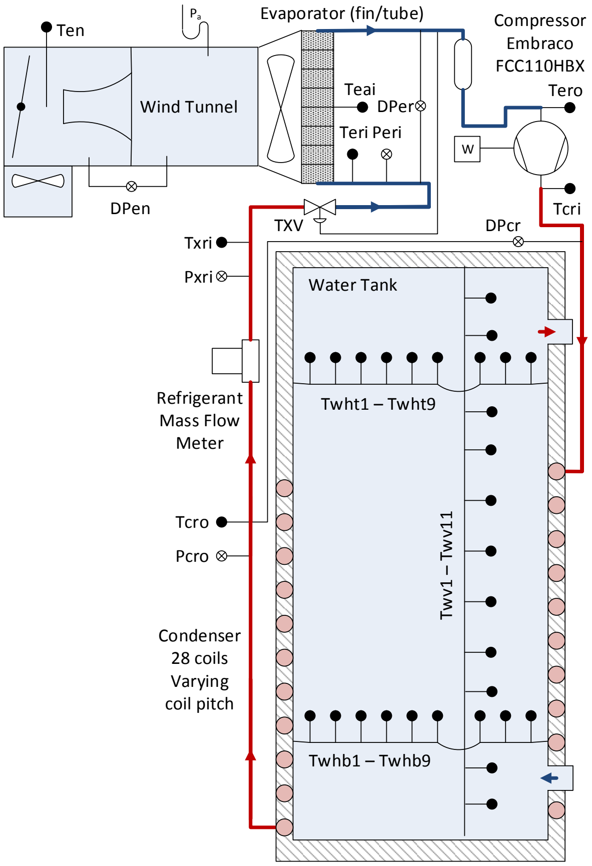

Figure 1: Schematic of instrumented HPWH in experimental facility.

Pressure transducers and T-type thermocouples have been instrumented at each state of the system. Thermocouples have been instrumented horizontally and vertically within the water tank in attempt to capture the temperature profiles within the tank. Compressor power is also measured. A wind tunnel is extended on the evaporator to measure evaporator capacity while maintaining ambient pressure around the evaporator. The unit is placed inside an environmental chamber with that maintains constant ambient temperature by adding heat as the system cools during operation. Air-side and refrigerant-side energy balances can be obtained for the evaporator, and water-side and refrigerant-side energy balances can be obtained for the condenser. The system will be used for future validation activities.

2. SYSTEM MODEL DESCRIPTION

2.1 General Modelling Approach

Two primary expected behaviors form the basis of the modelling approach: First, a quasi-steady-state assumption is made due to slow nature of the heating process. To capture the dynamic progression of the vapor compression cycle, the heating time is discretized into several steady-state time intervals by way of the quasi-steady-state assumption. Second, buoyancy forces drives fluid motion in the water tank. As a consequence of this second assumption, an upward flow stream is defined near the tank walls, and a downward flow stream is defined in the remainder of the tank. This fluid motion is driven by the buoyancy effects of higher temperature fluid, with lower density, rising to the top of the tank by displacing lower temperature fluid. The overall vapor compression system model was built using Engineering Equation Solver (EES). A key output from this system model is the amount of heat transfer from each coil to the water in the tank.

For each steady-state time interval, curve fitted spatial profiles for average velocity and average temperature in the water tank are inputted into the model in addition to the thickness of the upward flow stream.

The remainder of the inputs are design parameters and various specifications of various components. Certain parameters of interest are condenser coil geometry, refrigerant selection, and evaporator and compressor sizing. Once a validated linked model is developed, selection of these parameters can be explored by way of sensitivity analysis under various modes of operation, i.e. full warm-up, high temperature cycling etc.

2.2 Condenser / Water Tank Modelling Details

The condenser is a coil that wraps around the walls of the water tank. Superheated refrigerant is configured to enter the topmost coil and leave subcooled through the bottommost coil. The condenser is defined to have N coils, and each coil is discretized into M elements as shown in Figure 2.

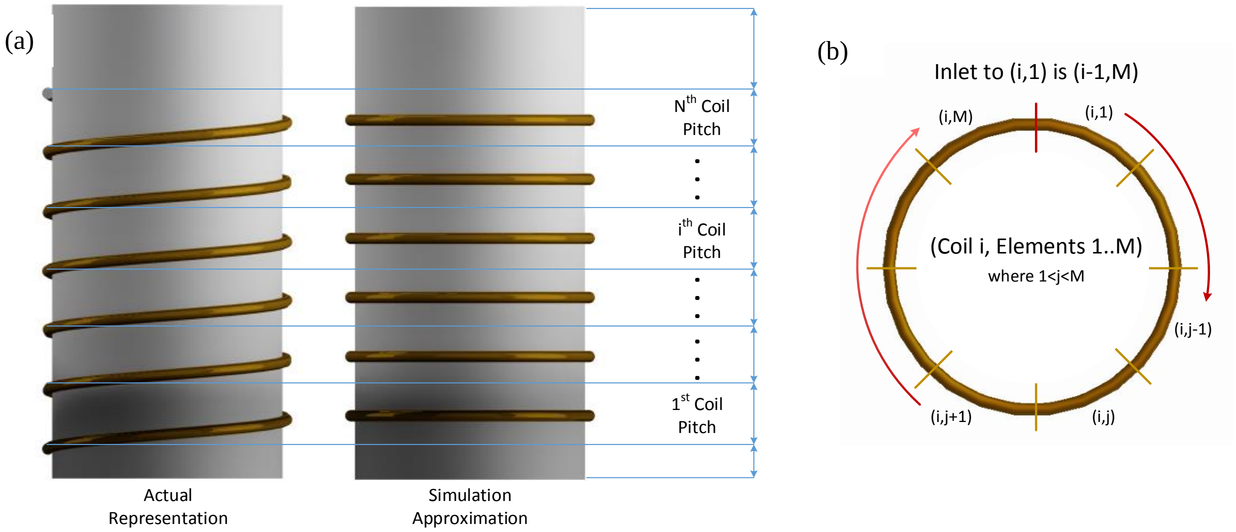

Figure 2: (a) Adaptation of coils windings in modelling, (b) Discretization of each coil into elements

The modelling of each coil element is shown in Figure 3. Each coil element has a corresponding segment of tank wall and upward flow stream annulus in a cross flow arrangement. This three-part arrangement thus consists of the refrigerant-side coil, the tank wall, and the thermal contact between the coil and the wall. The height of the tank is determined by the coil pitch as defined in Figure 2. These three parts and their resistances also define the heat path in the condenser. The refrigerant coils and the water tank walls are then each simplified to be fins in external flow as shown in Figure 4. The value for contact resistance is estimated with generally available data on contact resistances. In reality, this value may also take on a dynamic behavior due to the expansion and contraction of the refrigerant coils with changing temperatures in the condenser.

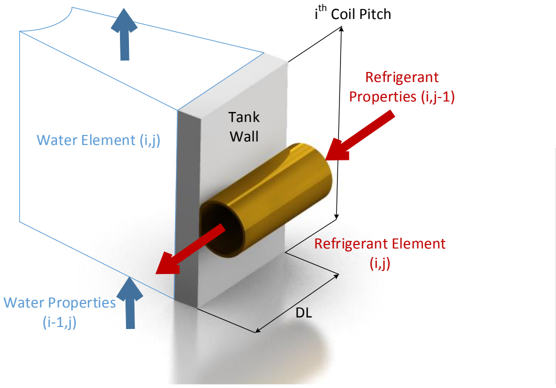

Figure 3: Single element of condenser.

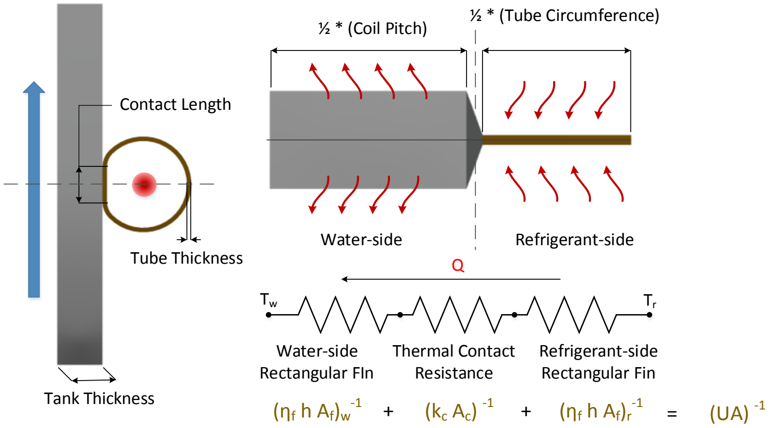

Figure 4: Element level modelling simplification and description of heat path.

3. CFD MODEL DESCRIPTION

3.1 CFD Overview and Methods

A separate CFD model for the water in the water tank during the heating process is built using ANSYS Fluent software. For the purposes of this model, the water tank is simplified to a two-dimensional (2-D) axisymmetric geometry as shown in Figure 5. 2-D axisymmetry can be assumed about the axial centerline of the cylindrical water tank as consequence of the adaptation of coil windings in Figure 4(a).

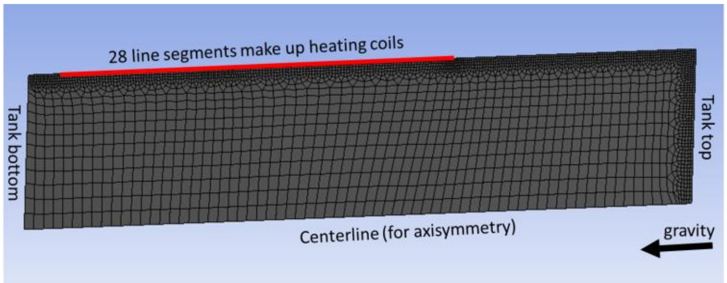

Figure 5: CFD geometry.

Each coil is accounted for by a line segment that represents the tank wall. The length of each segment is the respective coil pitch of that corresponding coil. The model then assumes that for each segment, heat is passed to the water uniformly on the surface of the segment. The inputs to this model are the temporal heat flux profiles for each coil by Fluent’s User Defined Function (UDF) feature. Key results of the CFD are temperatures and velocities of the water at various positions inside the tank at various points in time. Use of CFD also allows for the accounting of bulk water temperature with respect to time during simulation.

The transient or unsteady simulation was conducted with a second order formulation and a pressure-based solver. SIMPLE scheme is used for pressure-velocity coupling. Boussinesq approximation is used for computing density. Laminar flow is assumed to simulate the expected buoyancy driven flow. The mesh is refined near the tank wall and tank top to more precisely capture the water recirculation during the heating process.

3.2 General Trends

Below in Figures 6 and 7 are velocity pathlines and temperature contours respectively of water after 1 hour of heating. These figures are shown as an example to illustrate to fluid motion and temperature during the system operation.

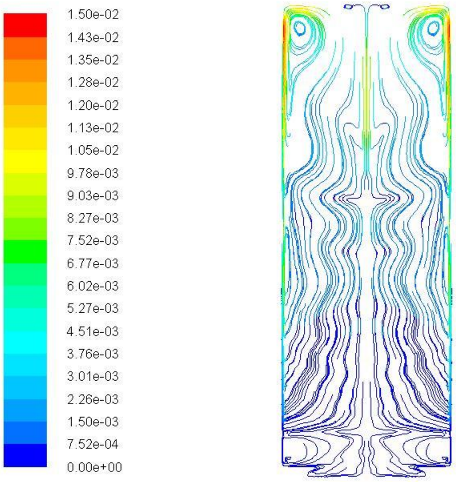

Figure 6: Velocity pathlines (m/s) of water in tank at 3600s.

Two important observations from the velocity pathlines are high upward velocities near the tank wall and velocity magnitudes generally increasing with height along the tank walls. Furthermore, these observations can lead us to define a thickness for the upward flow stream near the tank walls. This thickness would be incorporated in the system level heat transfer calculations.

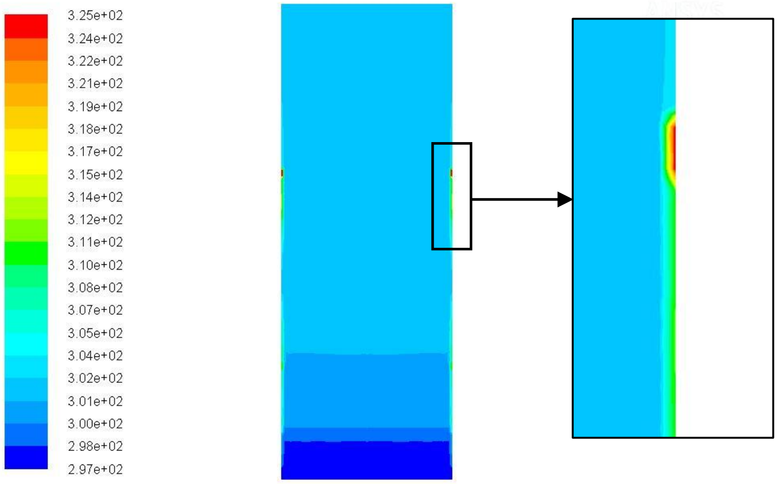

Figure 7: Temperature contours (K) of water in tank at 3600s.

Similarly, the temperature contours show higher temperatures in the upward flow stream near the tank walls due to the presences of the coils. Since the water is acting as the cooling medium for the condenser, water temperatures near the tank wall may affect overall system performance and condensing temperatures and pressures. At this point in time, the beginning of thermal stratification is also apparent.

4. LINKED MODELLING

4.1 Concept of Linked Modelling

The rate of heat transfer through the condenser can be calculated using Equations 1-5 below. As a result of the dynamic nature of the system, changing flowrates and temperatures on either the water-side or refrigerant-side will affect the respective heat coefficients on either side. Consequently, UA, temperature difference, and thus the heat transfer rate are subject to change on this basis.

$$Q = UA\,\Delta T_{lm} = \varepsilon(UA)\,C_{min}\,\Delta T_{in} \tag{1}$$
$$UA = \frac{1}{R_r + R_c + R_w} \tag{2}$$
$$R_r = \frac{1}{(\eta_f h A_f)_r} \tag{3}$$
$$R_c = \frac{1}{k_c A_c} \tag{4}$$
$$R_w = \frac{1}{(\eta_f h A_f)_w} \tag{5}$$

The system model already predicts refrigerant-side conditions on a finite volume basis thoughout the length of the condenser coil. Moreover, the proposed linked modelling attempts to take into account the evolution of local water-side temperatures and flowrates in time for each coil. This is accomplished by using local water-side information from CFD results to calculate instantaneous heat transfer rates, using the EES system model, for each coil at various points in time during which steady-state is briefly assumed. The newfound heat transfer rates are then inputted back into the CFD simulation to obtain updated water-side information and to start an iteration process that would ideally converge. Figure 8 depicts the interdependency of the two models as they interface at the tank wall on the water-side.

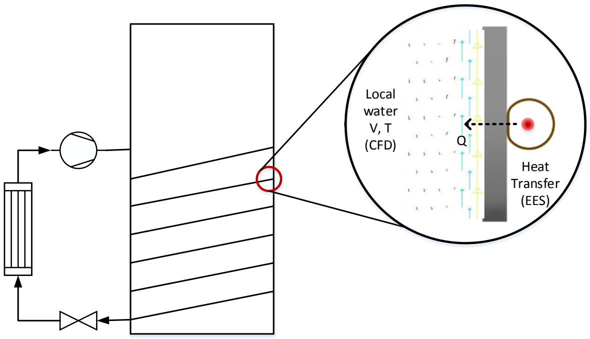

Figure 8: Interface of CFD model and EES system model at water-side tank wall.

4.2 Linking Algorithms

As a consequence of the required inputs of both models, linked modelling would allow for simulations to be representative of real system operation. To implement the linked modelling, an iteration procedure is needed that feeds heat flux profiles to the the CFD model from the system model, and velocity and temperature profiles to the system model from the CFD model.

The first linking algorithm is based on dividing iterations in the space domain as shown in Figure 9(a). In this case, the space domain constitutes as the coil architecture. In this model, a transient CFD is run for the full expected duration of the water heating process. Then, the CFD results are discretized into various time intervals, and the steady-state system model is run for each of the time intervals. The result of each iteration is an updated heat flux profile as a function of time for each coil. The heat flux profiles are then updated in the CFD and the iterations repeated again until the residuals of the profiles after each iteration begin to approach zero.

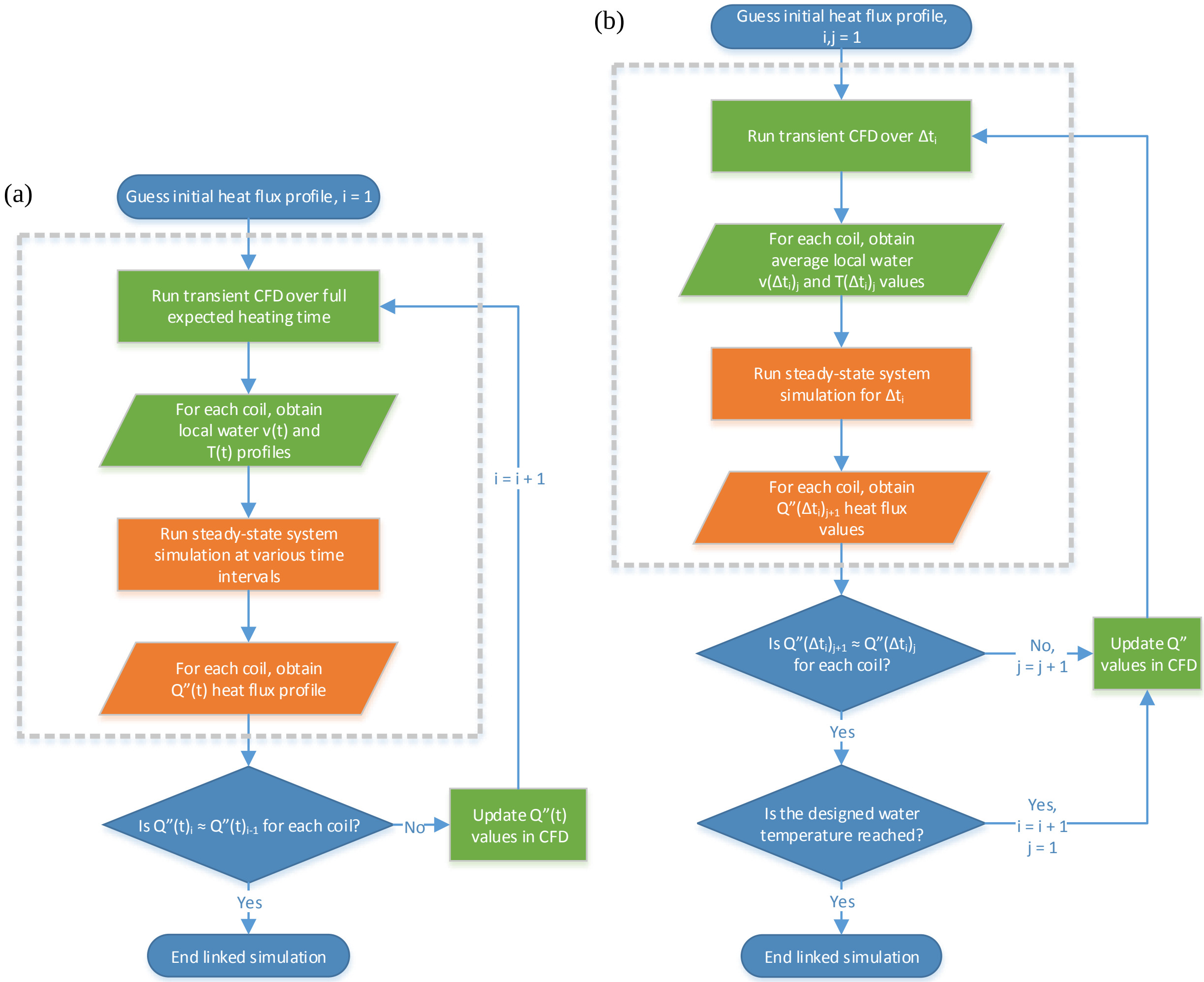

Figure 9: Linking algorithm 1, iteration in time

The second linking algorithm is based on dividing iterations in the time domain as shown in the flowchart in Figure 9(b). The essence of this model is first to select a steady-state time interval for which the system model can produce a heat flux profile, and then to run a transient CFD simulation within that time interval that will produce temperature and velocity profiles. In each iteration, the respective profiles are passed between the respective models. Once the residuals of the profiles after each iteration begin to approach zero, iteration for current time interval can stop and begin for the next time interval.

The linked modelling will thus produce functions in time of heat flux, water velocity, and water temperature for each coil.

5. VALIDATION PROCEDURE AND INITIAL DATA

5.1 Testing and Validation Procedures

Three types of tests are of interest. The first test is a full warm-up in which the tank is filled with cold city temperature water and heated to a desired hot water temperature setpoint. This test is intended to be representative of operating conditions just after load periods of heavy hot water demand, such as hot baths or showers.

The second test is a high-temperature cycling test in which the system shuts off once the setpoint is reached and the heat that is concentrated at near the top of the water tank is allowed to diffuse to the bottom of the tank and to the ambient. Once the temperature at the top of the tank, as measured by the onboard electronics, is far enough away from the setpoint the heat pump will turn back on to restore the setpoint temperature.

The third test is a high-temperature cycling test with water draw in which the system shuts off once the setpoint is reached and hot water is drawn from the top of the tank while cold water is returned at bottom. Once again, as the temperature at the top of the tank, as measured by the onboard electronics, is far enough away from the setpoint the heat pump will turn back on to restore the setpoint temperature.

Future simulations will be attempted to replicate each of the above three tests, and the simulation results will be compared to corresponding experimental results as part of the model validation.

5.2 Initial Experimental Data

A comparison of model results with experimental results will be conducted for each of the three tests. Predicted cycle states will be compared to experimental cycle states. Specific areas of interest are capacity, condensing temperature and pressure, and warm-up time.

Some initial experimental results from a full warm-up test are shown below. Figures 10 and 11 show the evolution of the pressure-enthalpy and the temperature-entropy diagrams, respectively, over the duration of the water heating operation.

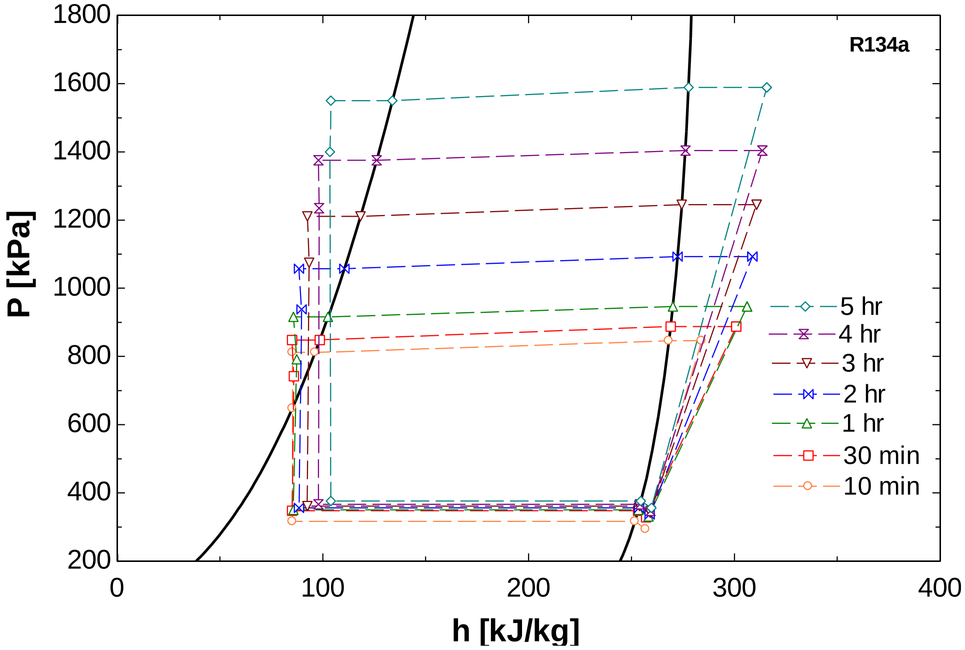

Figure 10: HPWH Pressure-Enthalpy over a full water warm-up from 23 to 51 degrees C.

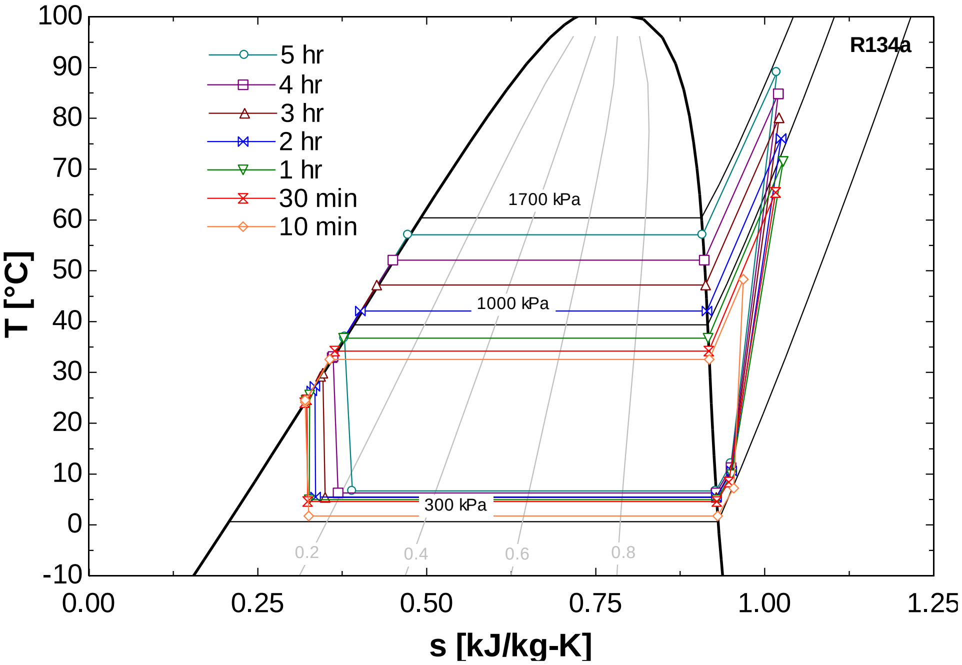

Figure 11: HPWH Temperature-Entropy over a full water warm-up from 23 to 51 degrees C.

6. SUMMARY AND CONCLUSIONS

In this study, a simulation model was developed for heat pump water heating system that involves the linking of a quasi-steady-state vapor compression system model and a transient CFD model of water in the water tank during the heating process.

As seen in the CFD simulation results, temperatures and velocities of the water near the tank wall change during the heating operation and vary from coil to coil. This dynamic behavior in turn, affects the spatial heat profile of the system in time, which again alters the fluid dynamics and heating in the water tank. This phenomenon affects the heat transfer rates on a coil by coil basis in the condenser as well as system level performance. As a result, the linked model was developed to take both phenomena into account.

The validation of the linked model is still in progress. Validation will be conducted with each of the three operating modes described in 5.1 Testing and Validation Procedures.

NOMENCLATURE

Abbreviations:

COP	coefficient of performance
CFD	computational fluid dynamics
EES	Engineering Equation Solver
HPWH	heat pump water heater
UDF	user defined function
TXV	thermal expansion valve

Symbols:

A	area (m^2)
Q”	heat flux (kW/m^2)
Q	heat transfer rate (kW)
V	velocity (m/s)
T	temperature (°C)
H	height from tank bottom (m)

Subscripts:

r	refrigerant
w	water
f	fin
c	contact
xri	expansion valve refrigerant inlet
eri	evaporator refrigerant inlet
en	evaporator nozzle
ero	evaporator refrigerant outlet
eai	evaporator air inlet
cri	condenser refrigerant inlet
cro	condenser refrigerant outlet

h	heat transfer coefficient (kW/m^2-K)
t	time (s)
Δt	steady-state time interval (s)
U	overall heat transfer coefficient (kW/m^2-K)
η_f	fin efficiency
k_c	contact resistance (kW/m^2-K)
R	thermal resistance (K/kW)

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