Steam Condensation in Packed Beds – An Experimental Study

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ABSTRACT

The performance of passive safety systems, in particular, passive heat removal systems is critical for advancing safe nuclear energy in the world. The upcoming light water reactors in design or deployment stage have passive heat removal systems, and steady steam condensation is one of the critical technical requirements to ensure that in most of the designs. A new design of packed bed steam condenser is proposed to ensure steady state heat condensation process for passive heat removal. In order to examine the basic physics associated with this design, the condensation on a randomly packed bed of spherical alumina particles was experimentally studied. This experimental setup ensures controlled condensation process without introducing significant changes in the thermal state or material characteristics of heat sink. The additional benefit of this experimental data would be to validate thermal-hydraulic codes. This data will have reduced spatial inhomogeneities as compared to steam condensation on walls and tubes, thus uncertainties will be reduced. Steam fronts at different flow rates were introduced in a cylindrical packed bed and thermal response of the media was observed. The temperature profile in the bed was monitored using a multi-point thermocouple assembly. Simultaneously, the wall temperature of the bed was measured with an infra-red camera. The obtained high-resolution temperature data was used to create polynomial-regression based supervised learning models for predicting the wall surface temperatures at unknown locations in different experiments. This process helped to understand and model thermal resistance from the packed bed to the container walls. The governing heat transfer modes in the media are completely dependent upon the rate of steam injection into the system. A distinct differentiation between the effects of heat conduction and advection in the bed were observed with slower steam injection rates.

KEYWORDS
Passive Safety, Steam Condensation, Two phase flow

1. INTRODUCTION

Across the world, energy demand continues to grow at a steady rate along with a growing need to replace fossil fuels. In this scenario, nuclear energy remains an important and viable energy option for the future, but this option would likely be jeopardized if more severe reactor accidents were to occur. Recently designed and licensed nuclear power reactors possess significantly more advanced active engineered safety features to reduce the probability of such severe accidents, but the ultimate solution to allay the doubts about nuclear energy rests in passively, or inherently, safe reactors. Inherently safe small modular reactors were envisioned many years ago [1]. These initial passively safe designs were based on both sustaining a long-term subcritical state of the core in all circumstances, and long-term heat removal without any forced circulation requirements. Some of the new reactor designs, and retrofitted existing reactors, have added some passive cooling features, but the knowledge of their behavior envelope in case of unexpected natural events is inadequate. The fundamental basis for passive cooling design is that upon loss of forced circulation, fuel temperature should remain substantially below the melting temperature. As upon safe shutdown, the decay of fission products is the only mode of heat injection into the core, any passively cooled design should be capable of removing this decay heat. There are three possible passive heat transfer modes for the decay heat removal: conduction, radiation, and natural convection. One or more of these modes are required to reject heat from either the core, reactor vessel, or reactor systems and transfer it into the external surroundings. This process of heat rejection in most of the designs is a two-step process. In the first step, the decay heat is transported from the core internals either to the surface of the reactor vessel or to some other system that can directly interact with environment. Next, heat is transferred from the reactor vessel surface, or similar component, to the atmosphere via radiation or natural convection. This latter step is largely dependent upon civil construction, effective exposed surface area, and external conditions where there is limited scope for significant design improvement. Therefore, the first step is critical for thermal-hydraulic design basis and better understanding of the internal passive heat transfer modes within the reactor systems can substantially improve design. Therefore, the confidence in the passive safety systems can be established by understanding and testing heat transfer processes from core in accident like situations for next generation reactors or improvised existing reactors. Most of the operating reactors across the world are water-cooled reactors and heat removal from the core is accompanied with sensible heat or latent heat transferred to water. Loss of Coolant Accident (LOCA) and associated severe accident scenarios in water-cooled reactors have been investigated for decades [2-6], resulting in models who's predictive accuracy is often contingent upon an understanding of complex two-phase flow phenomenon.

Several next generation nuclear plants such as Small Modular Reactors, upcoming Generation III+ reactors, and existing nuclear power plants, have passive heat removal design capabilities for long-term decay heat removal with continuous natural circulation. In such designs, during the heat removal stage from core the coolant i.e. water is expected to change phase and get converted into steam. This steam or two-phase mixture with lower density will undergo natural upward draft and after being condensed on other equipment and structures in reactor system will flow downwards and complete the two-phase natural circulation path. The example designs of different passive safety systems such as isolation condensers (IC) and containment spray systems, shown here in Figure 1, are detailed in IAEA report [7]. Isolation condensers are designed to provide cooling to a boiling water reactor (BWR) core, where the steam produced in the core is sent through the IC to condense and return to the core as a passive safety feature to continuously cool the core.

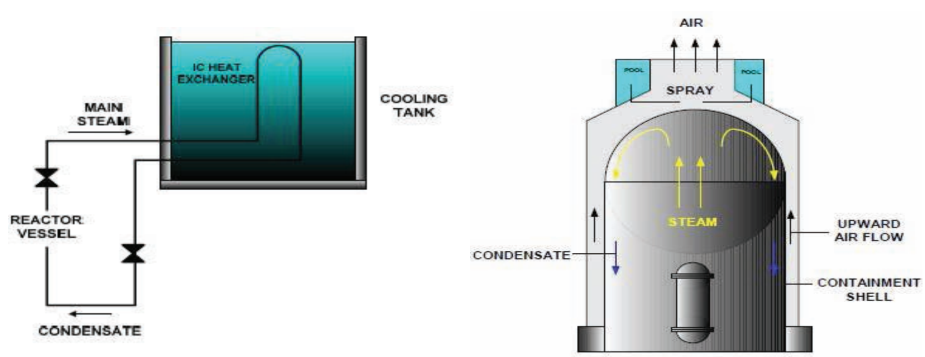

Figure 1. Schematic of isolation condenser for a BWR (left) and passive safety spray system and natural cooling draft air system (right) [7].

Similarly steam condensation on the containment walls of AP1000 reactor is important design feature to ensure the closed loop circulation after a break in coolant system. The condensed water can in turn be stored in reservoirs, which can be connected with IC heat exchanger loops or spray systems for continuous cooling of the core, primary coolant, and containment. Therefore, in all these examples the stable two phase natural circulation flow behavior is contingent upon steady, condensation-based heat rejection mechanism to a heat exchanger, containment walls, or any other geometrically complex system outside the reactor core. The already complex condensation process is accompanied with more complicated phenomenon such as transient thermal transport on containment walls, stratification of two phases, formation of discontinuous films etc.

A new packed bed isolation condenser design is proposed to reduce uncertainties in steam condensation process and improve passive heat removal capabilities of next generation LWRs. The packed bed isolation condenser comprises of small spherical alumina particles (1-3 mm diameter) which are chemically inert and have high energy density to act as long term heat sink. The schematic of packed bed isolation condenser with advanced BWR reactor is shown in Figure 2, where the packed bed is isolated above and connected to the reactor vessel via closed valves. In the case of an emergency the top safety valve will open allowing the steam to flow through the pipe to enter the top of the packed bed and condense over the alumina particles into water. The condensate then exits the bottom of the packed bed and returns to the core by gravity completing the natural circulation loop. The heat rejected into the alumina particles will be slowly dissipated to the surroundings from naturally cooled walls of packed bed.

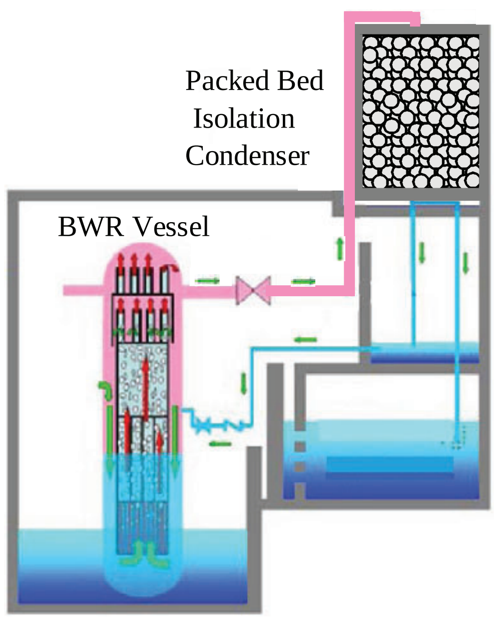

Figure 2. Schematic of alumina packed bed isolation condenser for a BWR.

In order to test this hypothetical design an experimental setup was developed to examine thermal behavior of such alumina packed bed upon steam injection. The experimental data from this steam condensation in packed bed can also be used for validating the existing thermal-hydraulic codes. Some of the previous experimental studies on steam condensation in containment had spatial non-uniformities, which did not resolve the issues about reliability of design [8-9]. The separate effect experiments are required to understand condensation-based heat rejection mechanisms [9]. The prime need is to design experiments where the vapor, steam, or two-phase mixture is expected to flow uniformly over the spatial domain and is expected to have higher degree of repeatability. The repeatability of the undertaken experiments and the quality of data obtained for validation purposes can be substantially improved if the phase change or heat rejection process are also uniform over the spatial domain. Moreover, different modes of heat transfer such as conduction and convection with or without phase change should be decoupled in experiments. This experimental study investigates the effect of rate of steam injection on the spatio-temporal heat transfer modes in the bed.

Steam condenser designs rely upon indirect heat exchange with secondary fluid or external environment. Therefore their design parameters are obtained from steady state empirical correlations for steam condensation and two-phase flow. With the availability of many powerful regression and classification tools, these empirical correlations can be replaced with spatio-temporal data learning models. These studies aimed to correlate the temperature of the center of the bed to the wall temperature and predict the thermal behavior of the bed or wall using regression based data learning techniques.

2. EXPERIMENTAL SECTION

2.1. Design Objectives

The design of the packed bed isolation condenser for passive heat removal spurred from previous experiments that utilized the vessel as a thermal energy storage system using alumina particle packed bed with air as heat transfer fluid by Bindra et al. [10]. These previous results showed that packed bed configuration enables the cross-sectional uniform flow and heat transfer distribution in the direction normal to the flow. Alumina particles, i.e. packing media have high heat capacity, high thermal conductivity and chemical inertness which allows the rapid localized equilibration of thermal energy between fluid phase and solid phase. The material is also non-degradable allowing it to last a long time and remain stable through multiple heating and cooling cycles. Large heat transfer surface area due to considerably smaller particle or packing size as compared to the overall bed dimensions makes the thermal front propagation more predictable and very steep along the flow direction. With saturated steam as the heat transfer fluid, rate of heat rejection is much faster during condensation process, thus if the media has sluggish response to absorb heat this will lead to very complex energy balance in three phases. Therefore, for this design the smallest possible alumina particles, which could be procured easily, were chosen to provide high surface area per unit volume of the bed. In case of accident like situation in light water reactors, where there is a loss of forced circulation two scenarios can be postulated- instant flashing and release of vapor in the containment after LOCA, and continuous vapor generation during long term decay heat recovery process. Both of these scenarios have very different rate of heat and mass injection, thus one of the objectives was to design an experimental set-up, which has capabilities to do both. The vessel to house alumina particles was made of quartz tube sealed with ceramic flanges at both ends to provide lowest possible energy dispersion effects from the boundaries. The visual inspection of motion of liquid-vapor interface can be done with the quartz tube and known constant emissivity value of quartz material which allows easy measurement of wall temperatures with IR camera.

The objectives of this study are to experimentally simulate the conditions for steam or vapor condensation in the abnormal conditions in reactor operation, thus exact state of the fluid phase i.e. fraction of liquid entrained or stream pressures can vary. Therefore this system is designed to handle more realistic scenarios where two phase mixture i.e. partially condensed steam can be the injection fluid stream. Our experimental goals are to show that alumina particle packed beds can be a viable option for nuclear reactors to incorporate inherent and passive safety features in the event of a reactor accident needing heat removal from the coolant.

2.2. Experimental Setup: Steam Condensation over Alumina Packed Bed

All experiments were performed in a cylindrical vessel randomly filled with spherical particles. The size of the vessel was 15.24 cm tall and 6.35 cm diameter, the limitations on the size were only on the diameter because of the standard ceramic flanges used to seal the ends. The diameter of the alumina particles were

3-mm because this was the smallest readily available size for the material chosen and the largest ratio between the spheres and the cylinder tube diameters was desired.

The measurement set-up to attain the temperature values along the outside wall of the heat sink vessel was a FLIR infra-red camera. The packed bed temperatures were measured with a multi-point thermocouple specially made to record the temperature at six points spaced evenly, besides the bottom two points which was half the normal spacing, inside the packed bed. The multi-point thermocouple was positioned as close to the center of the bed as possible using a fitting screwed into the top flange of the vessel. Each thermocouple was numbered respective to its position from the inlet of the test chamber.

Steam was supplied to the top of the flow chamber after passing through a pressure regulator. A globe valve was situated just before the vessel to allow control of steam after the supply valve was opened to allow steam to pass through the regulator. This combination allowed the system's response to a step input of constant pressure steam to be evaluated. Once the steam had passed through the flow chamber, it was passed through a tube-in-tube heat exchanger where and remaining vapor was condensed. This extra step allowed for the total mass of steam that passed through the chamber to be collected and measured, enabling a value for the total amount of energy input into the system to be obtained. A simplified schematic of the experimental setup is shown below in Figure 3.

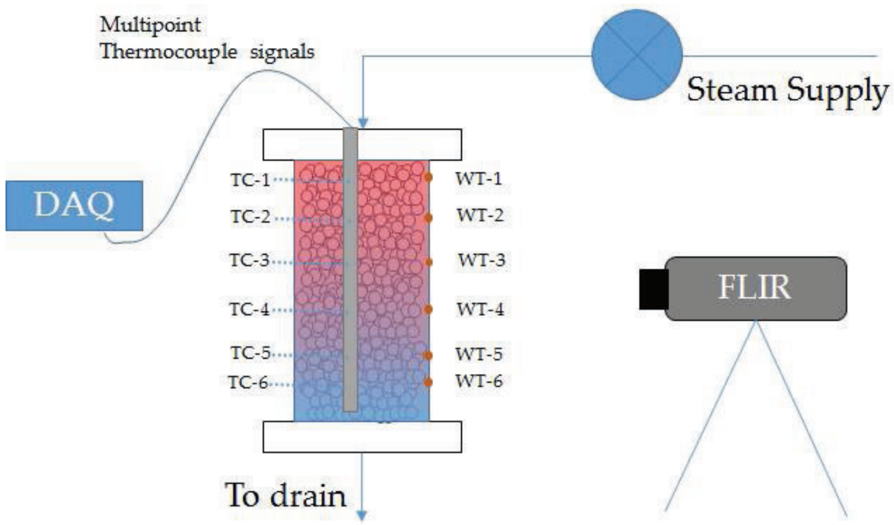

Figure 3. Schematic of experimental setup of packed bed heat sink consisting of a clear fused quartz tube, alumina particles, multi-point thermocouple, steel piping, steam supply, and FLIR camera.

2.3. Experimental Procedure

Two sets of experiments were performed. In the first set of experiments i.e. slow injection experiments, steam was first throttled by a globe valve to nearly atmospheric pressure before being injected into the top of the cylinder. This throttled condition was confirmed by the fact that the maximum temperature of the steam at the top of the cylinder did not rise significantly above 100 °C. For each of the slow injection tests, the cylinder containing the alumina was filled with water before the steam was injected. Steam was then continuously passed through the cylinder until such point as the thermographic camera registered that the wall of the cylinder had achieved steady state conditions.

In the case of the fast injection tests, the test chamber was first ensured empty by flowing dry, pressurized air through the packed bed. After the correct initial conditions were achieved – that of the alumina particles being both dry and at room temperature – and after setting the desired steam inlet conditions, a ball valve was quickly opened to inject the relatively higher pressure steam into the system. Unlike the aforementioned slow injection tests, for the fast injection experiments the steam was allowed to flow through the packed bed and exit out the bottom into a discharge pipe. The steam was continuously injected into the system at the set pressure until the thermographic camera registered that the wall of the cylinder had achieved steady state conditions.

Pressures for the experiments were controlled by a pressure regulator in conjunction with the steam supply line. For the fast injection case this value was representable of the actual pressure, whereas in the slow injection case the globe valve greatly reduced the pressure to near atmospheric, as mentioned earlier. The back pressure at the regulator was set at 50 psi for these experiments. The injection flow rate of the steam for each case was determined by condensing the steam in each case, collecting the condensate, and timing how long the valve was open. Multiple experiments were run to ensure repeatability and consistent flow rate values for both the slow and fast injection cases. The average condensate collection flow rates for the slow and fast were measured to be, respectively, 1.25 cm^3/s and 45 cm^3/s. In the following section instead of exact flow rates, discussion will be made using the terms slow and fast injection. For each experiment it was found that uncertainty in the measurement of condensation collection flow rate is within 5% of the numbers stated above.

3. RESULTS

The justification for these steam condensation experiments was described in the introduction along with the requirements for uniformity of flow and condensation process in the packed bed. To observe this uniform heat rejection process in the bed with radial symmetry, thermal images of the cylindrical quartz walls were captured using the FLIR camera. The thermal images along the wall of the packed bed for one of the experiments is shown in Figure 4. Without the solid media in the vessel, the steam would circulate through the containment and condense randomly along the walls. With the solid media present, the thermal front propagation images at different times shown in Figure 4 reveal that the steam condensation over the packed bed is radially uniform. Therefore, qualitative and quantitative analyses using the data obtained can be done in axial direction (1-D) i.e. direction of steam flow.

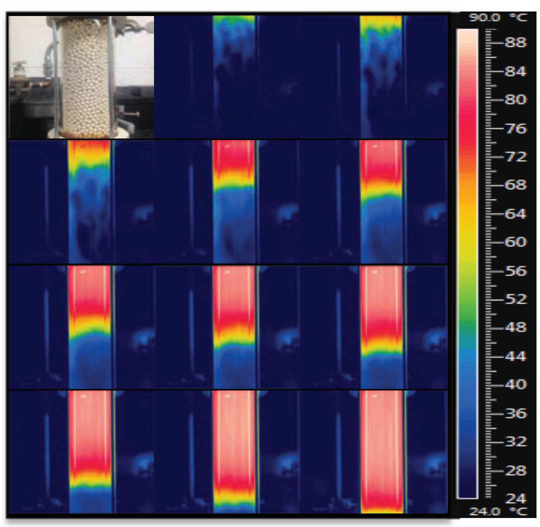

Figure 4. (TOP LEFT) Picture of experimental packed bed vessel. (THE REST) Time step images from FLIR software for an experimental run at 50 psi for; 5, 10, 15, 20, 30, 35, 40, 45, 50, 60, 70 seconds after steam injection, respectively.

3.1. Thermal Response of Bed with Different Steam Injection Modes

Steam or vapor flow in hot porous media has been studied previously using convection diffusion models in the past [11-12]. Radially symmetric time dependent one-dimensional convection-diffusion equation can be written as

$$\frac{\partial T}{\partial t} + \kappa v \frac{\partial T}{\partial x} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{1}$$

$$\kappa = \frac{\{\rho C_p\}_f}{\{\rho C_p\}_{b+f}} \tag{2}$$

where T is the local temperature of bed and fluid stream, x and t are the axial dimension and time variable respectively, $\{\rho C_p\}$ is the energy density per unit time, subscripts f and b denote fluid and bed respectively, v is the fluid stream velocity and α is thermal diffusivity of the bed. Although at inlet condition, the fluid stream is saturated steam and possesses latent heat, for simplified discussion in mathematical form can be considered as specific heat spread over the small temperature difference around the evaporation temperature. It should be noted that this convection-diffusion equation is used to provide qualitative analysis of the results and detailed quantitative analysis will require more work in future. The $\kappa v \frac{\partial T}{\partial x}$ and $\alpha \frac{\partial^2 T}{\partial x^2}$ terms in Equation 1 are the advection and conduction terms, respectively. Assuming the temperature is zero at the exit or bottom of the bed, in the direction of the motion of the fluid the temperature gradient, $\frac{\partial T}{\partial x}$, is negative and the $\frac{\partial^2 T}{\partial x^2}$ term is positive. Therefore at any axial location in the bed both of these terms will lead to positive rate of change of temperature. In the following subsections, the impact of slow and fast injections of steam on the temperature front progression at the points of measurement will be described.

3.1.1. Slow injection

The characteristic thermal response of the packed bed system at different times upon slow injection of steam is highlighted in this discussion with explanation of results. In case of slow injection, there are two thermal transport mechanisms- advection and conduction modes at different spatial locations and different time frames. Near the entry port where steam is introduced, in this present experimental set-up from the top, in a very short time interval temperature of the bed and fluid streams become almost equal to the steam inlet temperature or saturation temperature. As steam supply is continuously available, irrespective of injection rate, with constant temperature conditions at inlet, this implies that bed temperature at the top is always maintained at saturation temperature. This constant bed temperature at the top will conduct heat from the top to the bottom of the bed due to non-negligible thermal conductivity of alumina particles and water in the bed i.e. conduction mechanism. Simultaneously, due to steam injection in the bed it is carrying some amount of energy as it moves in the bed i.e. advection mechanism.

Due to slow injection rate, initial rise in the temperature at axially farther locations will be dominated by the conduction mechanism. As the steam or two phase mixture front, which is at temperature near the saturation temperature, reaches those regions located far away from injection point there is a sudden change in the temperature. This effect can be visually seen from Figure 5, with temperature measurements at different times and different locations. The rate of increase of temperature at different locations is divided into two distinct regimes with two distinct slopes for last four (3-6) locations. The initial regimes, which show lower slope are governed by conduction mechanism and later regimes with higher slope, are governed by advection. These conclusions are substantiated with the observations that conduction dominates for longer times for locations at larger distances from injection point. Similar effects were quantitatively predicted and experimentally observed by Woods et al. in radial vapor flows around porous beds [11-12].

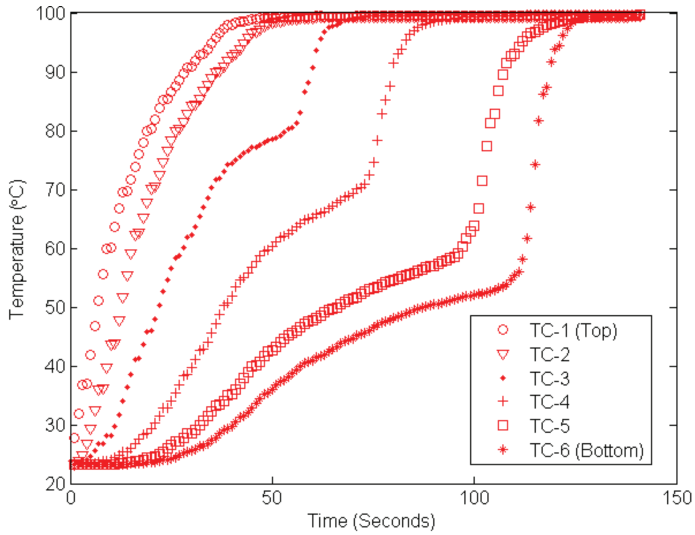

Figure 5. Thermocouple responses for slow injection experimental run.

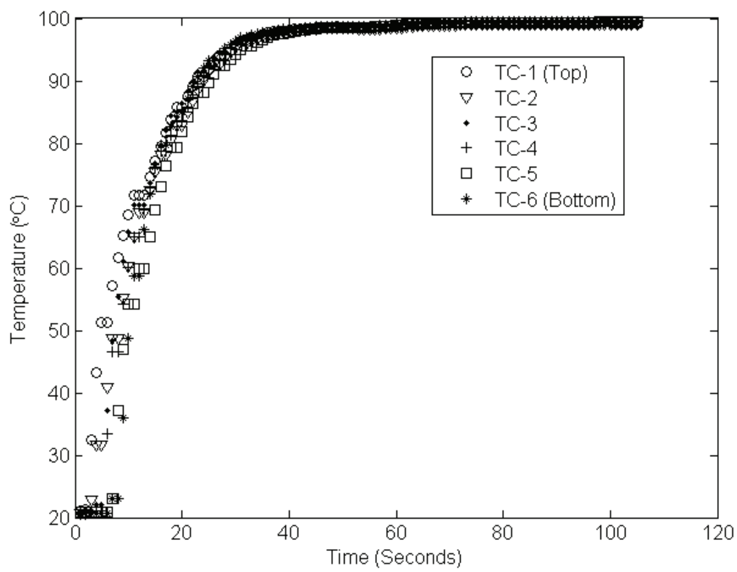

Figure 6. Thermocouple responses for fast injection experimental run.

3.1.2. Fast injection

Based on the explanations provided in previous subsection, it is expected that advection term will be much higher as compared to conduction term throughout the fast injection experiment. The higher advection term implies that total amount of influx enthalpy carried by the steam or two-phase mixture is much higher and thus, as the fluid stream moves through the bed it is equilibrating the bed to the saturation temperature at almost constant rate at all spatial locations. Due to much higher rate of enthalpy injection in the bed due to advection term, the effects of conduction will not have much impact on rate of temperature increase in the bed. The results in Figure 6, for fast injection, confirm this explanation.

As can be observed from the Figures 7 and 8 below, the response of wall temperatures (WT) (at same axial coordinates as those of corresponding thermocouples) as captured from IR camera also show similar temperature behavior for both fast and slow injections. In case of a packed bed steam condenser design, it is expected that the rate of heat rejection from the packed bed to the surroundings will be governed by heat transfer from the packed bed to the wall. If the bed temperature is in equilibrium or closer to the wall temperature, heat rejection to the environment is more efficient. In other words, the design of this passive heat removal device will be dependent upon thermal resistance between bed and the wall. Therefore to understand this resistance, spatio-temporal correlation between the bed temperature and wall temperature must be obtained. The difference between thermocouple temperature and wall temperature observations can thus be used to evaluate thermal resistance of the bed. In the next subsection, a regression methodology is presented and evaluated for thermal resistance predictions.

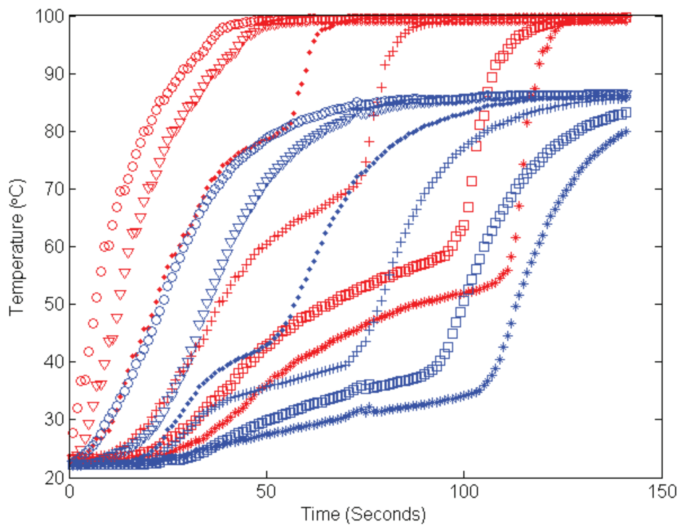

Figure 7. Thermocouple and wall temperature (Blue) responses for slow injection experimental run.

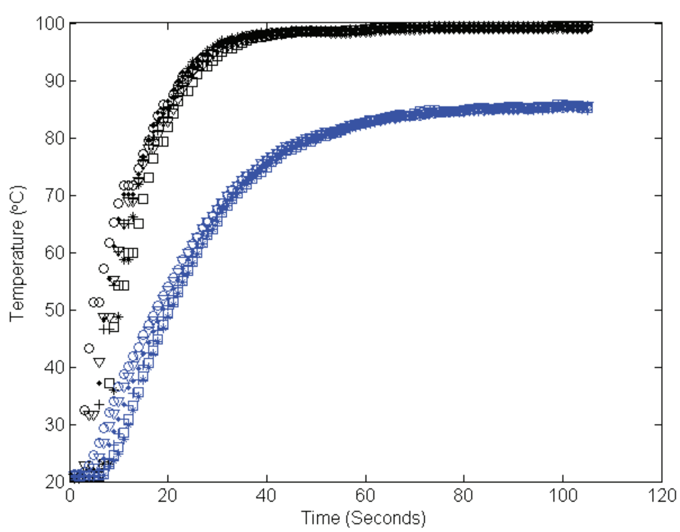

Figure 8. Thermocouple and wall temperature (Blue) responses for fast injection experimental run.

3.2. Polynomial Regression Analysis

The quantitative analysis of the temperature data from vapor flow over the packed bed experiments was done using supervised learning. The temperatures were obtained using the thermocouple and IR camera, as shown in previous subsection. The time steps of the thermocouple readings were every half second whereas the FLIR recorded thermal data 6.25 frames per second. In order to compare the two temperature data, the thermocouple data was interpolated using the MATLAB function *interp1* to fit it to the same time scale as the FLIR data. As described in the motivation of experiments, the temperatures in the center of the bed where the multipoint thermocouple assembly is located are the representative of equilibrium temperatures of moving fluid phase and stationary packed bed. However, the wall experiences a combined effect of heat losses to environment and thermal resistance between the bed and wall resulting into lower temperatures at all times for all experiments (Fig. 7 and 8). Various empirical models exist for computing thermal resistance in the beds for single-phase fluid transport without phase change and even those relations in the literatures have high degree of inconsistency. With the process of steam condensation and two-phase mixture flow, this inconsistency and inapplicability will increase further. Therefore, easiest approach is to develop data regression models and test their generic applicability. A polynomial regression model was developed between thermocouple temperature T_{ci} and wall temperature T_{wi}.

$$T_{wi} = a_0 + a_1 T_{ci} + a_2 T_{ci}^2 + a_3 T_{ci}^3 + \dots \tag{3}$$

$$\hat{a} = \left(C^T C\right)^{-1} C^T W \tag{4}$$

The coefficient vector $\hat{a}$ can be estimated using least square minimization as given by Equation 4, where, C is the matrix of thermocouple temperatures with different exponents and different times, and W is the vector of wall temperatures at different times. This was done using MATLAB function *polyfit*, and polynomials were fit to the temperature data for each thermocouple and corresponding wall position. These polynomials were then used to predict wall temperatures at different locations or in different experiments using *polyval* function of MATLAB and compared against actual measurements. The coefficient values for a slow injection experiment are provided in Table 1 below.

Table 1: Coefficients of Position 1 Polynomial for Slow Injection Case.

a_0	a_1	a_2	a_3
-1811.34	283.038	-17.7617	0.589969
a_4	a_5	a_6	a_7
-0.01123	0.000123	-7.21E-07	1.75E-09

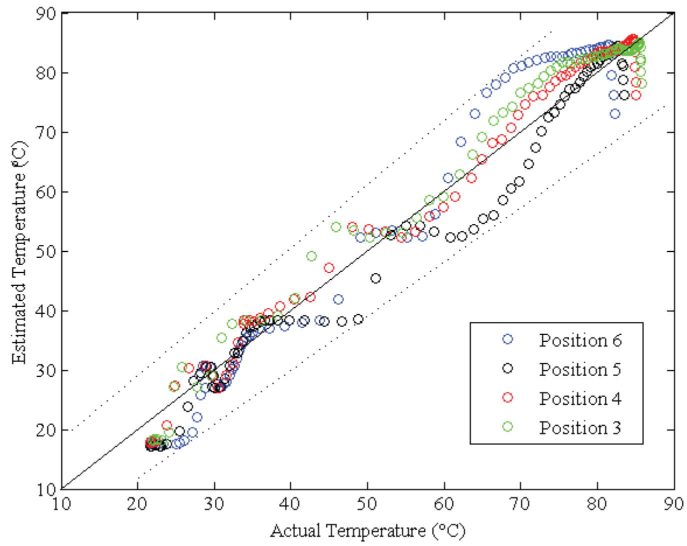

Figure 9. Actual wall temperature to estimated wall temperature for different positions using polynomial found for position 1.

3.2.1. Predicting wall temperatures

Using the functions *polyfit* and *polyval*, wall temperatures at the different axial locations were predicted using the polynomial obtained from relationship between wall and thermocouple temperatures at position 1 (i.e. top position). The predictor data i.e. thermocouple temperatures at different locations (positions 3, 4, 5, 6) were used in *polyval* function to estimate the respective wall temperature. From the plots in Figure 9, it can be inferred that accuracy in predicting wall temperatures decreases as the distance from position 1 increases.

Similarly, wall temperatures at position 6 were predicted using the polynomials derived using wall temperature measurements as training inputs at all six positions. Figure 10 shows the normalized errors between actual measurements and predictions for different training inputs. The error is greatest for predictions using training data from farthest location. The normalized error is as high as 30% for this case, but decreases if the training data location is nearer.

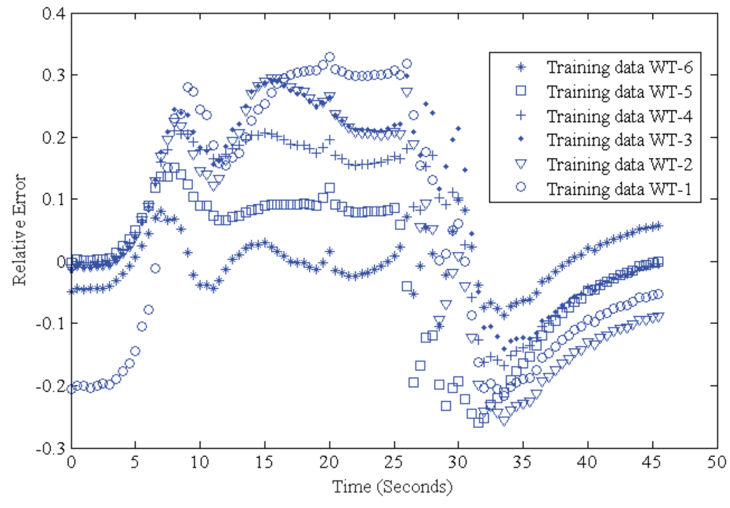

Figure 10. The error using the polynomial found for each position on the temperature data of just the first positon.

3.2.2 Using data-trained polynomial on another experiment

The polynomials were obtained with regression algorithm applied at different pairs of thermocouple-wall temperature locations in one experiment to make predictions of wall temperatures in other experiments. The comparative plots in Figure 11 between the actual measurements and predictions for wall temperatures in case of slow injection experiments show how close the model could predict another experiment.

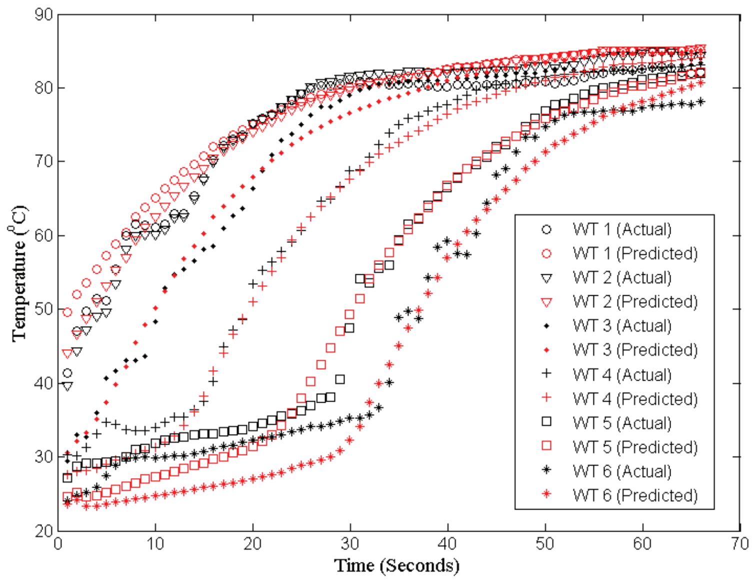

Figure 11. The comparison of actual and estimated wall temperatures for the second experiment using the polynomial model found from the first experiment.

It can be inferred from these results that training models obtained from one spatial location and an individual experiment have good capabilities in predicting temperatures at other spatial locations and experiments. But, it is difficult to suggest that a universal trained model can be obtained from these experiments. It is however envisioned that in the future the laboratory scale experiments can be designed to produce data trained models which capabilities for predicting scenarios at plant scale.

4. CONCLUSIONS

A new packed bed isolation condenser design is presented for passive heat removal in next generation LWRs to ensure steady condensation process and passive circulation. In order to test basic principles of this design, a steam condensation heat transfer experimental set-up was designed using packed bed of alumina particles. The IR camera images of experimental runs show that the steam condenses with cross-sectional uniformity over the packed bed of spherical particles in the directional plane normal to the steam flow, justifying the design basis. Steam condensation on walls and in tubes is often associated with spatial inhomogeneities which can lead to high degree of uncertainties. Uniform steam condensation experiments on packed bed allow better spatial control over condensation process. This high fidelity data can also be used for validating steam condensation thermal-hydraulic models which are generally used for modeling the existing nuclear safety systems. The experiments were conducted with two modes of steam injection- fast and slow mode. Thermal response of the bed was found to be distinct in both of these cases. In case of slow injection mode, the temporal behavior of the bed was found to be divided into two spatial zones, advection driven temperature rise in the bed near the steam injection point and conduction driven temperature rise for the regions far from the injection point. As the slow moving steam front reaches the far zone, then it sees steeper rise in the temperature during later stages of the experiment. Fast injection mode involves high enthalpy flux penetrating and equilibrating the bed quickly, thus only advection driven temperature rise is observed at all spatial locations. Heat transfer to the packed bed during the steam condensation in the vessel is expected to flow radially through the vessel walls to the environment, therefore internal heat resistance should be quantified in order to understand the actual design details. This internal heat resistance model during steam condensation in packed bed is developed using regression analysis on experimental data. Regression analysis was performed on the temperature data of the packed bed (thermocouple) and the temperature data of the wall (IR measurements) at corresponding vertical positions and times, to create the predictor algorithms that could be used on other locations or similar experiments to predict the wall temperatures. Patterns observed from these predictor models at each position in the packed bed, show that relative prediction errors grow as the distance between training data and prediction points increase. The performance of models were satisfactory when they were used to predict wall temperature in other experiments if the bed temperatures are given. In future experiments, a heater or evaporator will be added in a loop with the packed bed to generate a steady state natural circulation loop.

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