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Two Phase CFD Simulations in Stagnant Water Pools: Unsteady Temperature and Level Variation

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In the present work, CFD simulations of transient temperature increase in a pool of water due to indirect contact heating in the middle of the pool has been presented. CFD simulations have been able to mimic the transient phenomena of increase in temperature throughout the pool eventually leading to evaporation of water at the top surface and decrease in the level of the pool due to thermal stratification after several hours of operation. The CFD model is first validated with experimental temperature and water vapour volume fraction profiles at a particular level of the pool from the literature. Predictions show good agreement of less than 10% variation is observed. Spatial temperature profiles for different times are analysed to understand the pool boiling in such pools. The profiles indicate thermal stratification after 10000 seconds. Further, analysis transient variation of stratification parameter confirms the strong thermal stratification after 10000 seconds. The evaporation rate after 10000 seconds from top surface have been measured and compared with empirical models from literature

1. Introduction

Pool boiling in water pools and chemical pools has gained interest over the last two decades. In some applications (eg. safety applications in power plants) such pools have large header tube assemblies immersed in water which dissipate heat to the pools leading to heating up of water in the pool. With progress of time thermal stratification takes place and the water at the top get heated leading to vaporization and lowering of the water level in the pool. To avoid thermal stratification mixing needs to be incorporated naturally without the help of moving elements. While experimentation of such large pools cannot be done, they are performed in pilot scale pools as suggested by various authors (Sharma et al. 2008). Experimental data for transient temperature, pressure and level reduction due to evaporation of the water in the pool is obtained. In other applications such as chemical pools the evaporation rate of the chemicals lost to the atmosphere due to its volatility at atmospheric pressure is important (Mazzarotta and Bubbico, 2016). The evaporation rates are determined by empirical formulae or analytical expressions.

2. Literature review

The problem has primarily gained importance due to the absence of mixing and researchers have focused on the ways to promote mixing. Lab scale experiments have been performed by some researchers (Ganguli et al., 2010; Gandhi et al., 2013). CFD modeling have been performed by some researchers (Krepper et al., 2007; Ganguli et al., 2010; Gandhi et al., 2013; Minocha et al., 2015). A boiling model for nucleate boiling and validated the model with lab scale experiments in a cylindrical tank and single tube where heat dissipated was from steam condensation inside the tube by researchers (Ganguli et al., 2010). The model was extended to a lab scale set-up with header tube assembly kept in a rectangular tank (Gandhi et al., 2013). Improvisations for reducing stratification were suggested by introduction of draft tubes, inclination of tubes and enhancing mixing by bubble sliding motions (Gandhi et al., 2013; Minocha et al., 2015; Minocha et al., 2016). The parameter used to study the stratification has been the stratification parameter (Ganguli et al., 2010) which suggests the extent of stratification that is possible in all the above cases. Experimental work on pilot scale set-up has been

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carried out by researchers (Sharma et al., 2008) in which the actual large scale geometry was scaled down using scaling laws. The actual power requirement was reduced by 452 times and scaling of geometric parameters was done on this basis. The authors have carried out extensive experimentation for different levels and monitored the temperatures by keeping thermocouples at the top of the tank to monitor the increase in temperature with time. Similarly, level indicators have been placed at the top to understand the decrease in level of the tank. The authors have compared their experimental data with predictions of RELAP code. Substantial deviations from the RELAP code were observed. Most of the work reported in the literature has focused on minimization of stratification using draft tubes in the pools. In the present work an effort has been made to understand the capability of the model by simulating a pilot set-up. The objectives are (a) to validate the model results with experimental data of a pilot test set-up (b) to have an insight of the temperature patterns and profiles that take place during the heat dissipation in the pool (c) Compute the stratification parameter for the system and (d) find the predicted evaporation rate and compare with literature.

3. Geometry and numerical procedure

A rectangular geometry for the tank has been considered for the study. The height of the rectangular tank is taken to be the initial height of the water level. All the dimensions of the tank, the water level have been considered similar to that of literature (Sharma et al., 2008).

3.1 Geometry details and assumptions

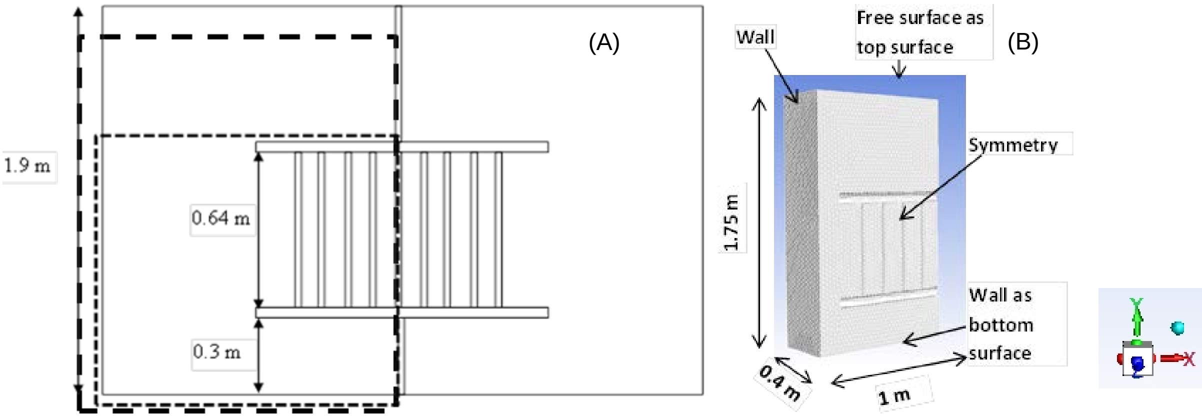

Figure 1: (A) Details of geometry used for simulations. Small dotted line represents the domain for simulations with initial height of 0.83 m and large dotted line represents domain for simulations with initial height of 0.83 m (B) Typical mesh used for simulations

Figure 1 shows the entire geometry as described in literature (Sharma et al., 2008). The computational domain considered for simulation is restricted only the dotted line. Three dimensional simulations have been done. Since there is symmetry on all sides of the geometry considered only one-fourth section of the domain was simulated. All assumptions of the earlier work (Ganguli et al., 2010) are considered. Two assumptions in addition to the earlier assumptions are as follows:
The fluid is incompressible and obeys boussinesq approximation.
Uniform steam distribution takes place inside the tubes

3.2 Governing equations, Mesh, Boundary conditions and Method of solution

Governing equations can be found in our earlier work (Ganguli et al., 2010). A tetrahedral mesh consisting of 551195 elements along with the boundary conditions and mesh are shown in Figure 1B. Mesh sensitivity was carried out with three grids 432,711 elements; 551,195 elements and 703,194 elements based on the axial centerline temperature in the pool after 100 seconds. The deviations between 551,195 elements and 703,194 elements have been found to be ~2.5%. Symmetry has been taken on two sides of the geometry while all other sides except top have been considered as wall. The top of the tank has been considered as free surface boundary condition. Unstructured mesh has been used to simulate the geometry under consideration. Heat Flux boundary condition is provided to the central tube entering to the top header, the top and bottom headers, the tubes and outlet tube as per literature data (Sharma et al., 2008). Ansys Fluent 14 has been used for all simulation activities. The discretization schemes for the continuity, momentum, energy and turbulence equations have been kept similar to earlier work (Ganguli et al., 2010). Convergence criteria has been maintained such that sum of residuals were 1e-05. Computations have been carried out in desktop PC's having good computational power. A single phase run took 60 days to reach 10000 seconds while a multiphase run took 90 days for a single run. The time step considered for both single and multiphase simulations was 0.00001 s to start with and was reduced adaptively to 0.05 seconds till it reached 10000 seconds.

4. Results and discussion

4.1 Model validation

The model has been validated with the experimental results for the header-tube bundle to be completely immersed in the pool with initial level of 1.75 m and 0.83 m and heat flux of 75 kW (Sharma et al., 2008). In Figure 2 the temperatures have been presented in degree Celsius for comparison with literature data. The temperature and level variation has been shown till a time of 10000 seconds for model validation since experiments showed that there was monotonous decrease in level after 7000 seconds for both initial water levels considered. This signified that validating the model within 10000 seconds would be enough to validate the model predictions about its robustness. Figure 2A-2D shows the comparison of CFD model results with experimental data from literature (Sharma et al., 2008) and RELAP code as per literature (Sharma et al., 2008). For the initial water level of 1.75 m the predicted temperatures by CFD agrees well within 10-15% deviation from experimental results.

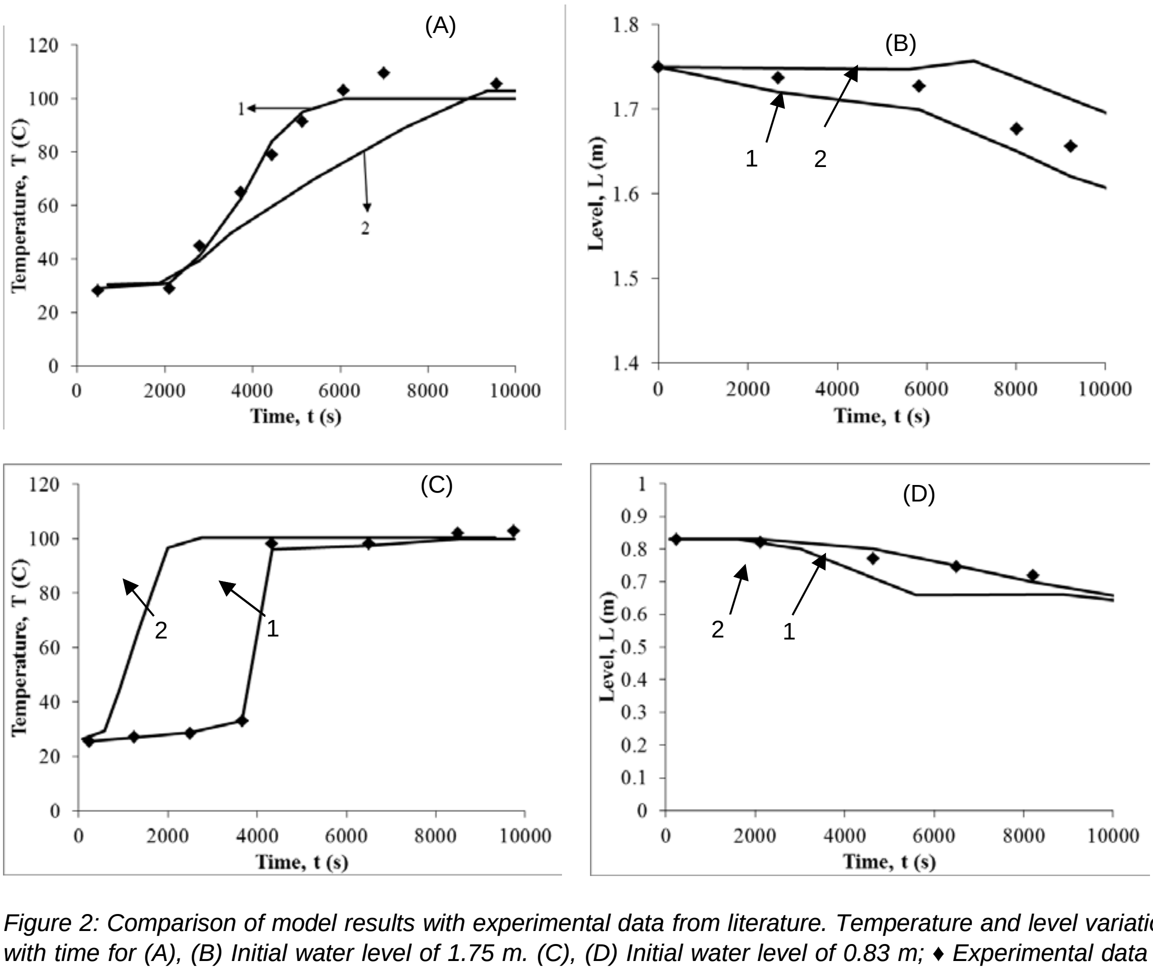

Figure 2: Comparison of model results with experimental data from literature. Temperature and level variation with time for (A), (B) Initial water level of 1.75 m. (C), (D) Initial water level of 0.83 m; ♦ Experimental data of literature (Sharma et al., 2008); 1. Present CFD Model 2. RELAP code

The temporal temperature predictions of CFD model are better than the ones predicted by RELAP code (Sharma et al., 2008). The temporal temperature predictions of RELAP code show deviations of 20% in the case of initial level of 1.75 m while the predictions for an initial level of 0.83 m are as high as 30%. The temporal level variations predicted by both the CFD model and RELAP code show deviations upto 10%.

4.2 Flow patterns

The investigation of flow patterns was done to understand the phenomena of spatial temperature variations and level variations during transition.

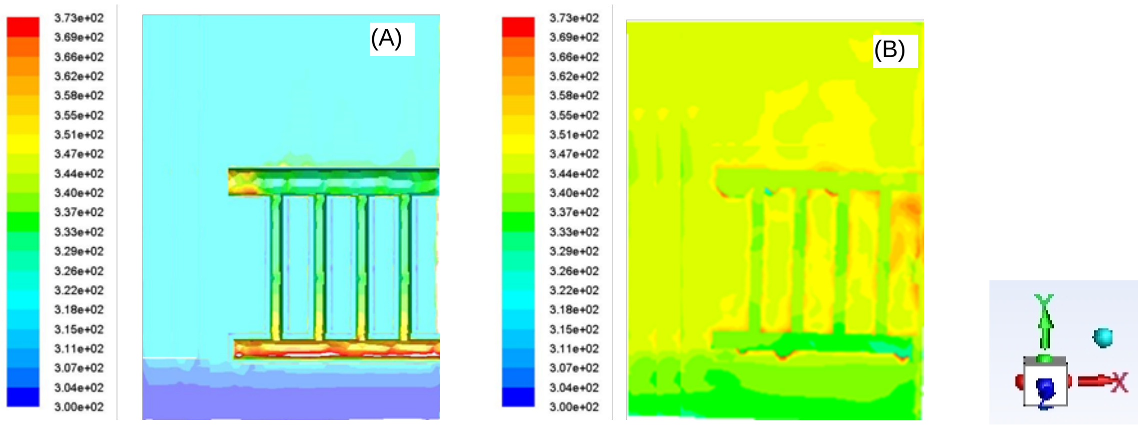

Figure 3: Temperature contours for the geometry for an initial height to 1.75 m and heat flux of 75 kW at symmetry plane z=0.01 m (A) t = 1000 s (B) t = 3000 s

Figure 3A shows the temperature contour at t = 1000 seconds at the symmetry boundary condition whether the header tube assembly is present. The figure depicts that till 1000 seconds the temperature stratification is limited to the region below the bottom header of 0.3 m. Though the temperature variation at different spatial locations in the z-direction away from the header tube assembly would be different it is important to note that the flow patterns comply with the fact of experimental observations where the temperature is flat till 2000 seconds. The temperature however continues to rise after 2000 seconds and at 3000 seconds there is a sudden jump in the temperature to more than 363 K. An effort was made to understand this sudden rise in temperature both with the help of temperature and volume fraction patterns. It is observed after t = 3000 seconds most of the pool in the vicinity of has reached a temperature of 323 – 333 K overall in the pool while temperatures at top reach around 348 K at the top. The volume fractions of vapour of reach to 0.75 at the top portion (Y = 1.75-0.5 m) at t = 3000 seconds as shown in Figure 4A. With increase in time, it is evident that the top portion has low temperature gradient and the heat gets concentrated at the top portion leading to high volume of bubbles/vapour between Y = 1.75 to 1.4 m reaching saturation temperature of water than the rest of the pool.

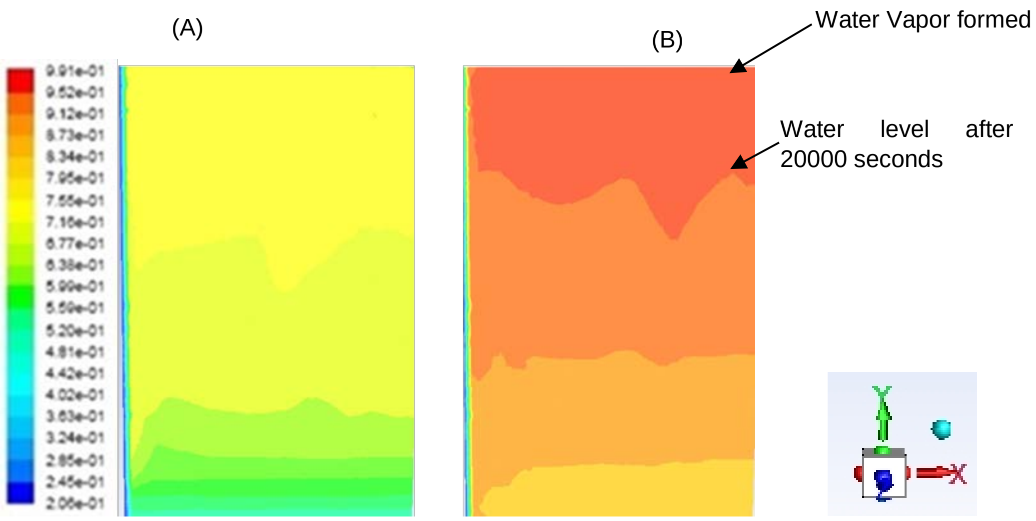

Figure 4: Volume fraction contours for the geometry for an initial height to 1.75 m and heat flux of 75 kW at z=0.2 m (A) t = 3000 s (B) t = 20000 s

Figure 4B depicts the volume fraction of vapour reaching 1 for a height Y = 1.75 to 1.62 m when the initial height at t = 0 seconds is 1.75 m. This confirms the experimental observations of Figure 2B where the level reduces to 1.65 m. A slight deviation is due to the free slip boundary condition at the air-water interface. More accurate results can be expected with front capturing methods like volume of fluids. However, such coupled three dimensional simulations would require high computational power and time

4.3 Temperature profiles and Stratification parameter

Figure 5 shows the axial/vertical temperature profiles for two positions of Z (Z = 0.2 m and Z = 0.3 m) and three different X positions at each Z (X = 0.25m, 0.5m and 0.75m) for two times (A) t = 3000 seconds and (B) t = 20,000 seconds. It is observed that the trend of increase in temperature for all points is linear till Y = 0.5 m from bottom with steep temperature gradient while at after Y = 0.5 m the temperature gradient lowers down. The disparity in spatial temperature distribution is slightly higher in the bottom (till Y=0.5m) where higher temperature gradient are present suggesting negligible mixing. The temperature increase from Y = 0.5 m to Y= 1.75 m is only 8 K suggesting that there is some amount of mixing. At t = 20000 seconds however, the lines temperature profiles are evenly distributed throughout the entire pool suggesting completely stratified pool. The top part (from Y = 1.25 m to Y = 1.75 m) is constant at 373 K suggesting that the portion of the tank is filled with vapour and there is a decrease in water level across the pool. This also matches the experimental predictions of level variation reported in the literature (Sharma et al., 2008).
With above information, the amount of stratification taking place in the tank has been quantified using the stratification parameter defined in the literature (Sharma et al., 2008). The stratification parameter varies from 0 to 1 with 0 representing no stratification or complete mixing and 1 representing maximum stratification. Figure 5 C represents a graph of stratification parameter versus time. The Z locations, X locations shown in Figures 5A and B have been considered for calculations of stratification parameter for each times. Further, the stratification parameter was calculated for each time interval of 2000 seconds from 0 to 20,000 seconds. The stratification parameter also confirms that complete stratification takes place after 6500 seconds and the water level goes on decreasing due to complete formation of vapour.

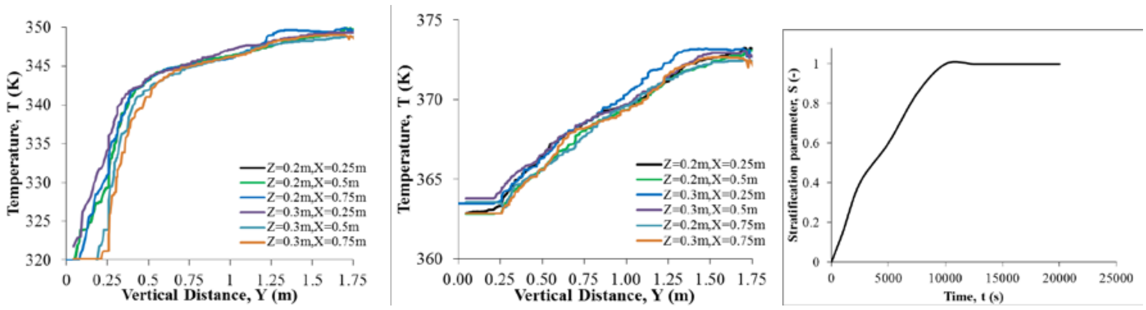

Figure 5 Spatial and temporal temperature variation. (A) and (B) represent axial temperature variation for two time instances t = 3,000 seconds and t = 20,000 seconds respectively and (C) Amount of stratification taking place quantified by Stratification parameter.

4.4 Evaporation rate

Literature *(*Mazzarotta and Bubbico, 2016*)* showed that mostly researchers have either calculated the mass transfer coefficient through empirical correlations to determine the evaporation rate or directly found evaporation rate empirically. The mass transfer coefficient considers the wind velocity while here the wind velocity is zero. In the present work an attempt has been made to find the experimental evaporation rate from literature *(*Mazzarotta and Bubbico, 2016*)* and compare with the evaporation rate predicted by CFD and two models which predict evaporation rate empirically. It was found that the CFD model under-predicts the evaporation rate by 13% while one of the empirical models under-predicts the evaporation rate by 43%. This is also in agreement with the comparison of models predicting evaporation rate shown in the literature (Sharma et al., 2008)

5. Conclusions

In the present work, three dimensional simulations of a pilot scale experimental setup for pool boiling has been carried out. The following conclusions can be drawn:

1. The model is able to predict both temperature and level variation with 10 to 15% deviations from the experimental data
2. The model predicts better than the RELAP code which is a one-dimensional code
3. Volume fraction flow patterns confirm that stratification is taking place in the pool leading to vaporization and decrease in the level.
4 Spatial and temporal profiles at two different times confirm that stratification is confined to the bottom of the tank initially but the tank is fully stratified at 20000 seconds
5 Quantification of stratification is done by the stratification parameter and its temporal variation
6 The model confirms its capability to predict flow patterns and spatial temperature, velocity and volume fraction profiles and can be used for scale-up studies

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