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Numerical Investigation and Measurement of Transient Two-Phase Boiling Flow

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Abstract
Transient boiling is examined for conditions related to the hypothetical heating of liquids in a storage tank by an external fire, with the potential for evaporation of the liquids and the release of toxic gases into the environment. Temperature and void fraction distribution data were obtained from an experiment on water heated in a tank. Numerical simulations were also performed. These generally agreed reasonably well with measurements.

Introduction
Transient boiling processes are encountered in many industrial applications such as in nuclear reactors, in steel production, and in electronics component cooling. In this study, the heating of liquid in a storage tank by an external heat source is investigated numerically and experimentally. Safety concerns arise if the inventory contains hazardous liquid chemicals and the tank is exposed to an external fire. This could lead to liquid evaporation and the subsequent release of toxic gases into the environment.

An experiment in which water was heated in a tank was performed at the Institute of Safety research, Rossendorf [1]. Temperature and void fraction distribution data were obtained as a function of time. Recently, numerical analyses of the tests were carried out [2] using the Computational Fluid dynamics (CFD) code CFX-4.4, developed by AEA technology [3]. The boiling model implemented in CFX-4.4 was applied, which is based on Anglart and Nylund [6] mean bubble diameter and Tolubinsky and Kostanchuk [8] bubble departure diameter. In the present paper as the second set of predictions was from the code modified to incorporate a more realistic boiling model recently developed at ANSTO [4,5]. Preliminary results are presented here. The boiling model is being further developed for better prediction of transient boiling of the type considered here.

Experiment Arrangement
The experimental test arrangement consisted of a 0.25 m high, 0.25 m diameter cylindrical tank (see figure 1). The initial water inventory was about 10 kg. The side vertical walls were heated by elements with an overall power of 4 kW. The heating power was uniformly distributed over the walls.

The tank was equipped with thermocouples (•) and conductivity probes (□). As shown in figure 1 and table 1, these measured local temperatures and void fractions at various axial and radial locations. Void data were obtained at wall distances of 1mm and at the cylinder centre; temperature data were obtained at wall distances of 1 mm and 10 mm. A third void fraction measurements line was made available, which was moveable in the horizontal direction. During the last part of the test, this provided a full radial distribution of the void fraction. The time dependence of the actual heat flux on the tank wall during the test is shown in figure 2.

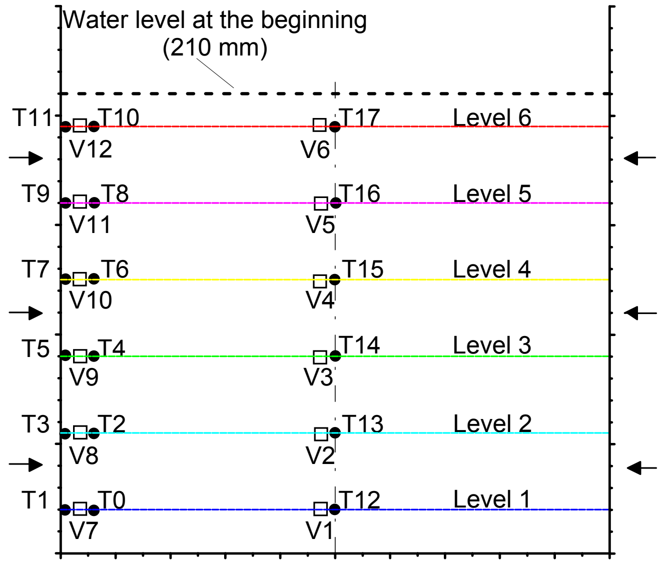


Figure 1. Spatial arrangement of the measuring probes.

Level	Height [mm]	Near the wall			Centre	
		1 mm		10 mm		
		Temp.	Void	Temp.	Temp.	Void
6	195	T11	V12	T10	T17	V6
5	160	T9	V11	T8	T16	V5
4	125	T7	V10	T6	T15	V4
3	90	T5	V9	T4	T14	V3
2	55	T3	V8	T2	T13	V2
1	20	T1	V7	T0	T12	V1

Table 1. Measurement locations of thermocouples and conductivity probes.

Two-Phase Boiling Model
A two-fluid model formulated in terms of two sets of governing equations for the balance of mass, momentum and energy of each

phase is used to predict the boiling process. A standard κ-ε model is employed to account for the turbulent boiling flow. The interaction of these two phases is effected through closure relationships such as inter-phase drag, heat and mass transfer terms in the field equations. These terms have been highlighted elsewhere (Anglart and Nylund [6], Tu and Yeoh [5]) and will not be repeated here.

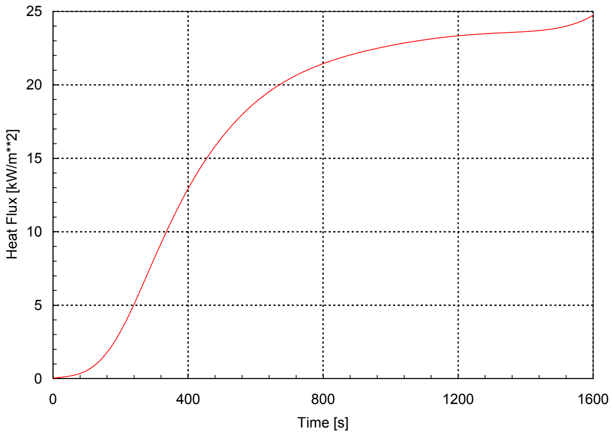


Figure 2. Experimental heat flux as a function of time.

The capability of the default and improved boiling models of CFX4.4 for boiling predictions are assessed in this study. In particular, relationships determining the mean bubble diameter in the bulk liquid and the bubble departure diameter at the heated wall are investigated. Under low-pressure subcooled flow boiling, the correct quantification of the partitioning of the wall heat flux at the boundary is required. Important physical processes of the heat partition model are briefly described.

Mean Bubble Diameter

In the existing model of CFX-4.4, the mean bubble diameter in the bulk liquid is modelled as a linear function of local liquid subcooling, as originally proposed by Anglart and Nylund [6].

In the alternative developed at ANSTO, the correlation developed by Zeitoun and Shoukri [7] is instead adopted because of its applicability for subcooled boiling flow at low pressures. Zeitoun and Shoukri [5] correlated their experimental data with:

$$\frac{D_s}{\sqrt{\sigma / g\Delta\rho}} = \frac{0.0683(\rho_l / \rho_g)^{1.326}}{Re^{0.324}\left(Ja + \dfrac{149.2(\rho_l / \rho_g)^{1.326}}{Bo^{0.487} Re^{1.6}}\right)} \qquad (1)$$

where ρ_l and ρ_g are the liquid and vapour densities and $\Delta\rho$ is the difference between ρ_l and ρ_g. Here D_s is the mean Sauter diameter; σ is the surface tension; and g is the gravitational acceleration. The non-dimensional parameters in equation (1) are Re, the flow Reynolds number; Bo, the boiling number; and Ja, the Jakob number. The mean diameter is estimated from the mean Sauter diameter.

Bubble Departure Diameter

The existing CFX-4.4 bubble departure relationship as a function of subcooling temperature is the empirical correlation of Tolubinsky and Kostanchuk [8].

In the improved model the bubble departure diameter correlation of Fritz [9] for low pressure is employed:

$$d_{Bw} = 0.0208\varphi\sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}} \qquad (2)$$

where φ is the contact angle, taken to be 80°.

Wall Heat Partition Model

Various experimental and theoretical investigations for low-pressure subcooled boiling flow (Judd and Hwang [10] and Victor et al. [11]) suggest that the wall heat flux has three components:

(i) heat transferred by evaporation or vapour generation, Q_e;
(ii) heat transferred by conduction to the superheated layer next to the wall (nucleate boiling or surface quenching), Q_q; and
(iii) heat transferred by turbulent convection, Q_c.

These are discussed further in [5].

Numerical Procedure

The tank was modelled in two-dimensional cylindrical coordinates. The steam released at the upper surface was modelled as a degassing boundary. It acts as a steam sink according to the rising velocity of steam and to the steam volume fraction.

A transient simulation of the two-fluid model, comprising two sets of governing equations for the balance of mass, momentum and energy of each phase, was performed. The conservation equations were discretised using the control volume technique. The higher-order QUICK scheme was employed for the advection. The velocity-pressure linkage was handled through the SIMPLE procedure. Time dependence was treated implicitly using the second-order backward differencing. The discretised equations were solved using Stone's Strongly Implicit Procedure [10] except for the pressure correction where Algebraic Multi Griding solver [11] was employed to accelerate convergence. Computational results were obtained on an uneven mesh distribution of 32 respective 40 (radial) × 32 respective 80 (height) with elements most densely concentrated near the boundary walls.

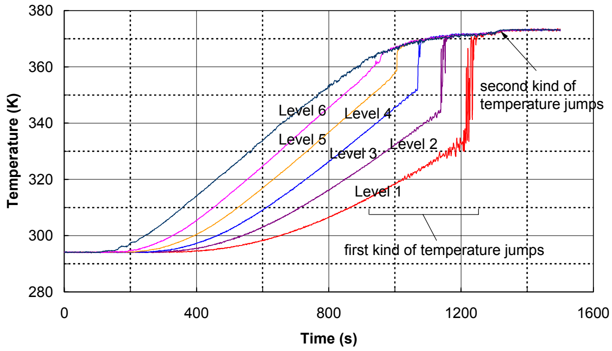
An iterative procedure was employed to evaluate the wall temperature on the heated side. The applied heat flux at the wall, q, partitioned into the three components described above, must satisfy

$$q = Q_q + Q_e + Q_c \qquad (3)$$

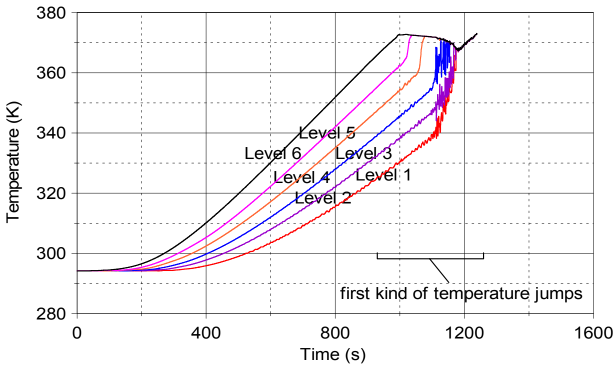
A bisection method was used to determine the tank wall temperature that satisfies equation (3). The iteration continued until the residual of equation (3) between the applied and calculated wall heat flux was less than 10^{-4} of the total heat flux.

Results and Discussion

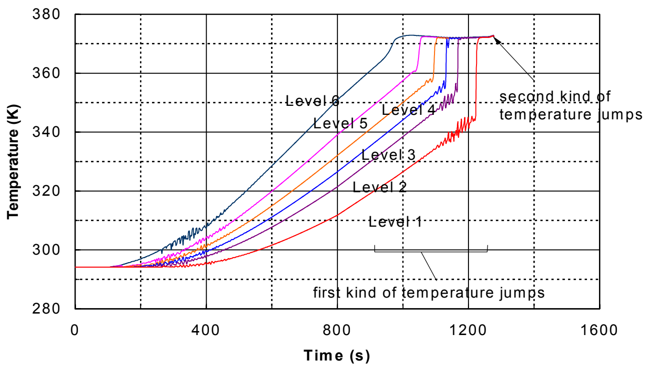
Figure 3 compares measured and predicted transient temperature profiles at the centre of the tank. During the first 900 seconds single phase heating up with a strong temperature stratification was observed and calculated. After the first occurrence of steam at the upper part of the heated side wall, the rising steam accelerates the fluid. The previously temperature stratified region is mixed up by the generated steam. A horizontally orientated boundary between upper well-mixed and lower temperature stratified region is established. During the further heating up process these boundary moves gradually downwards. When the boundary passes a thermocouple, a temperature jump is found. Temperatures jumped to about 370 K between 900 to 1200 seconds. This behaviour is denoted as the first kind of temperature jumps. Both predictions clearly replicated this phenomenon. A quantitative comparison shows, that the improved boiling model yields a better accordance to the experiment(see figure 3). More definite transitional temperature jumps occurred at levels 1 to 4. For the improved boiling model (see figure 3© at level 1 (the largest jump), the predicted ~ 40K jump compares favourably with the ~ 30K measured jump. Its experimental onset at about 1220 s is accurately predicted. The 1130 s at which the temperature jumped at level 2 temperature is also accurately predicted. The temperature jumps at levels 3 and 4 were predicted to occur marginally later than they actually did.



(a)



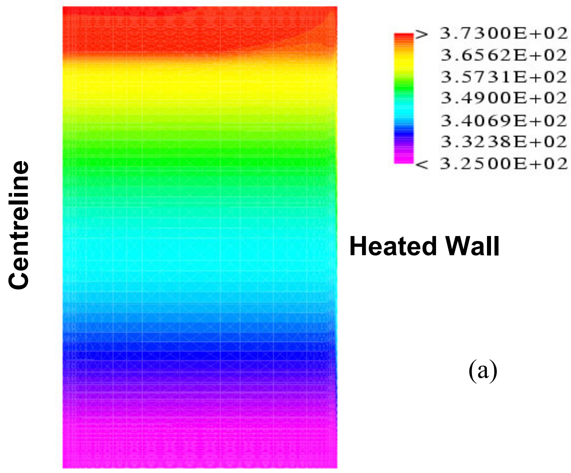
(b)



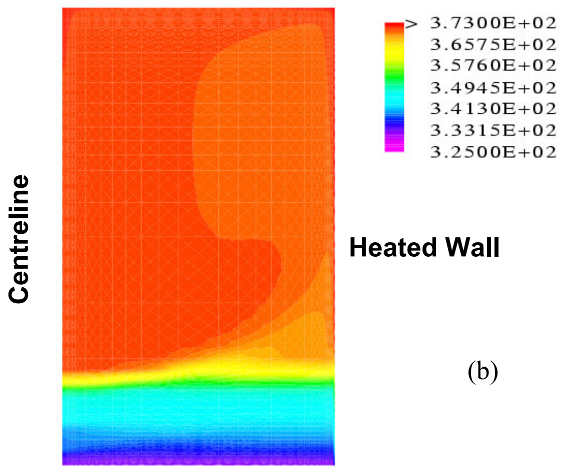
(c)

Figure 3. Measured (a) and predicted (b) (default CFX-4.4 boiling model) and (c) (improved boiling model) temperatures at the centre of the tank (Temperature thermocouples T12 to T17).

Figure 4 shows the calculated temperature distributions at 1000 s and at 1200 s. The stratification of temperature due to natural convection is clearly seen in figure 4(a). Here, the inception of nucleate boiling produced only at the heated wall a thin layer of rigorously upward moving fluid. At later times, more steam was generated, and the rising steam accelerated the fluid. The upper region becomes well mixed, whereas the lower region remains temperature stratified. Figure 4(a) shows the boundary between mixed and stratified region at about 80% of the height of the tank. As more heat was added to the tank, the boundary moves gradually downward. Figure 4(b) shows the boundary at about 20% of the height. When the boundary reaches the bottom and the whole tank is well mixed, pool boiling occurred and the second kind of temperature jump were observed. The two-fluid boiling model was reasonably successful in capturing the transitional state leading to the second kind of temperature jump However, after about 1280 seconds, the remainder of the phenomenon could not be simulated because of convergence difficulties.



(a)



(b)

Figure 4. Temperature distribution at: (a) 1000 seconds and (b) 1200 seconds. (Improved boiling model)

Figure 5 shows the measured and calculated local void fractions 1 mm away from the heated wall and at the tank centre. Both simulations fail with higher void fractions for numerical reasons. However, the improved boiling model (see figure 5(c)) predicted local void fractions that were comparable to those measured during the first kind of temperature jumps. At later times (>1280 s), this model also starts to predict unrealistic behaviour. More modelling work is in progress to extend the capability of the present boiling model to simulate the second kind of temperature jump.

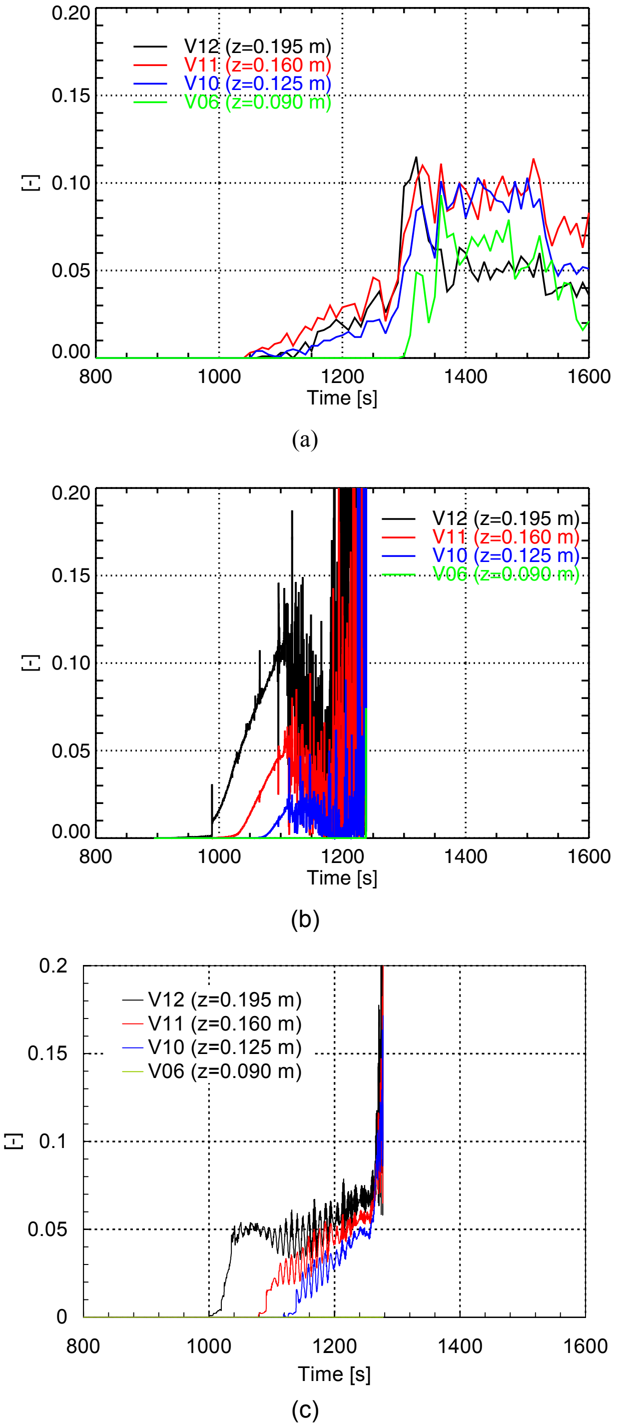


Figure 5. Comparison of local void fractions at 1 mm wall distance (V10, V11, V12) and in the centre (V06) (a) measurement, (b) CFX default and (c) improved CFX boiling models.

Conclusions

This paper presents experimental and numerical investigation of transient pool boiling in a storage tank subjected to heat applied on the vertical walls. Measured temperatures and void fractions at different locations showed interesting boiling phenomena and mechanisms of two-phase natural convection.

Model predictions were successful in predicting the first kind of temperature jumps observed during experiments. Numerical problems were however encountered in attempting to simulate the quick transition from slight subcooled to volumetric boiling that resulted in the second kind of temperature jumps.

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