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Numerical Investigations of Deteriorated Heat Transfer Phenomenon for Supercritical Water Flow in Vertical Tubes

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Abstract**—** The present paper is aimed at the in-depth thermal-hydraulic analysis of supercritical water flow at various operating conditions in vertical circular tubes. A one-dimensional thermal-hydraulic solution algorithm has been used for the analysis in this paper. Nine experimental cases are studied thoroughly and out of these, four cases which are operated at various working regimes are chosen and presented for the detailed analysis of deteriorated heat transfer and normal heat transfer cases. The studies are carried out for the distributions of nondimensional acceleration and buoyancy parameters, and different types of pressure drops along the axial direction and its effect on the heat transfer.

Keywords-supercritical fluid; deteriorated heat transfer; turbulence kinetic energy; buoyancy; acceleration

I. INTRODUCTION

The renewed interest for heat transfer and fluid flow analysis in supercritical fluids has been established since the supercritical water - cooled reactor (SCWR) has been identified as one of the six Generation IV nuclear reactors by Generation IV International Forum (GIF) [1]. The advantage of the SCWR over the Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) is the high thermal efficiency, avoidance from the boiling crisis, compact plant system and close proximity to the proven technology for supercritical fossil power plants (SCFPPs). Extensive studies of the heat transfer and fluid flow of water and CO2 at supercritical conditions have been conducted since 1950s, by several researchers [2–4] and detailed studies are also reported in numerous review papers [5–7].

Although the boiling crisis is avoided in SCWRs, there is large variation in thermo-physical properties of supercritical water, especially in the pseudo- critical region (PCR) and it is the major cause of the deteriorated heat transfer(DHT) which results in a severe increase in the wall temperature. Therefore, the detailed knowledge about the DHT is very important for the design of a SCWR. The unusual heat transfer phenomenon in the PCR is also attributed to the enhanced buoyancy and acceleration effects on the heat transfer. The buoyancy effect is a result of a decrease in the density whereas the acceleration effect generally results from the increase in the thermal expansion coefficient. The DHT has been widely investigated by the researchers. Till the date, there is no effective tool to analyze the DHT phenomenon for broad range of operating conditions due to enhanced buoyancy and acceleration effects, and abrupt changes in thermo-physical properties in the PCR.

Several experimental studies have been performed to find the accurate empirical correlation for the heat transfer coefficient in the supercritical region [2–4] which can be implemented in 1-D thermal-hydraulic codes. The detailed reviews of these studies on the heat transfer in supercritical fluids were given by several researchers [6, 8, 9].

Buoyancy, flow acceleration and sharp variation of transport properties at the supercritical condition, mainly in the PCR, can adversely affect the flow dynamics leading to the suppression of turbulence and thus, cause the significant reduction in the heat transfer locally. The theoretical studies conducted by Mikielewicz et al. [10] and Sharabi and Ambrosini [11] confirmed that the buoyancy and sharp variation of transport properties at a low mass flux condition played the major role behind the occurrence of the DHT phenomenon rather than the flow acceleration. Liao and Zhou [12, 13] experimentally studied the supercritical behavior of CO2 in mini tubes of different diameters and found that the effect of buoyancy parameters decreases as the size of the tubes decreases. Similar studies conducted by He et al. [14] proved the insignificance of buoyancy at low Reynolds numbers for supercritical fluid flows in mini tubes. Jiang et al. [15, 16] during their studies of supercritical fluid flow in mini tubes found that both buoyancy and flow acceleration influence the flow conditions, but the flow acceleration plays the dominant role. Jiang et al.[17], while performing an experimental investigation on supercritical pressure CO2 in a vertical micro tube, quantitatively determined the effects of the thermal (A_t^*) and compressible (A_p^*) acceleration parameters separately and found both are comparable for that specific condition. The effect of the buoyancy parameter was found to be have negligible impact for the micro tube and therefore, attributed the cause of reduction in heat transfer to the acceleration parameter. All these studies [10, 11–17] dealt with the cases where the low mass flux condition was prevalent.

In the present study, the numerical investigation of the fluid flow and heat transfer in vertical tubes is performed using the 1D Thermal-Hydraulic solveR Undertaking Supercritical waTer (THRUST) code. The 1-D model is developed in-house. It was earlier used to simulate boiling water reactors (BWR)[19], and was extended and validated for SCWRs in the previous study [18]. Several parameters, which were earlier proposed to predict the occurrence of DHT are tested in the present study to verify their applicability in different working regimes and are also used to predict the occurrence of the deteriorated heat transfer zone (DHTZ) inside the channel. Buoyancy and acceleration at a low mass flux condition are generally considered to be responsible for DHT. Attempts are also made to investigate the effect of pressure drops due to different factors on the occurrence of the DHT phenomenon.

II. Mathematical details of Thrust

A. Mathematical Formulations and Solution Methodology

In the 1-D TH model, it is assumed that the thermo-physical flow properties vary along the axial direction only and the heat flux at the periphery of the circular tube is constant. The conservation equations are solved numerically using a spatially fixed grid structure. The fundamental one-dimensional governing equations for the fluid flow under the steady state condition are as follows:

Mass conservation equation:

$$\frac{\partial}{\partial z}(\rho A u) = 0 \tag{1}$$

Momentum conservation equation in the axial direction:

$$\frac{\partial}{\partial z}(\rho A u^2) = -A\frac{\partial p}{\partial z} - \tau_w P_w - \rho A g \tag{2}$$

Energy conservation equation:

$$\frac{\partial}{\partial z}\left(\rho A u e_f\right) = q_w P_H \tag{3}$$

where $e = e_f - \frac{p}{\rho}$ and $e_f = h + \frac{u^2}{2} + gz$. The equation of state, $\rho = \rho\,(p, h)$, is also used.

The resultant discretized equations are as follows:

$$\rho_{i+1}A_{i+1}u_{i+1} = \rho_i A_i u_i \tag{4}$$

$$p_i - p_{i+1} = \frac{1}{2}\left(\frac{1}{A_i} + \frac{1}{A_{i+1}}\right)[(\rho A u^2)_{i+1} - (\rho A u^2)_i] + \frac{1}{2}[\{\rho(F+g)\}_i + \{\rho(F+g)\}_{i+1}](z_{i+1} - z_i) \tag{5}$$

where $F = \frac{\tau_w P_w}{\rho A}$

$$(e_f)_{i+1} - \left(e_f\right)_i = \frac{1}{2}\left[\left(\frac{q_w P_H}{\rho A u}\right)_i + \left(\frac{q_w P_H}{\rho A u}\right)_{i+1}\right](z_{i+1} - z_i) \tag{6}$$

The above set of equations, in addition to the equation of state, are solved numerically by using a forward marching scheme when all the inlet primary variables, i.e., inlet velocity, enthalpy and pressure are specified, otherwise a shooting method along with the forward marching scheme is employed to treat different set of specified conditions.

B. Parameters to Analyze DHT

The accuracy of 1-D TH models largely depends on the appropriate selection of correlations for friction factor and heat transfer coefficient (HTC). The Filonenko correlation for the friction factor and three HTCs provided by Swenson et al. [3] (HTCS), Watts et al. [20] (HTCW) and Mokry et al. [21] (HTCM) are used in this study. The previous study [18] verified the applicability of the above mentioned HTCs by comparing the numerical results with the experimental data.

Different parameters used in THRUST to predict the occurrence of the DHT and DHTZ are described below.

Buoyancy parameter, B^*, is defined as follows for the real fluid, which is widely used in the literature [10] to account for the effect of buoyancy at a low mass flux condition.

$$B^* = \frac{Gr_b^*}{Re_b^{3.425}Pr_b^{0.80}} \tag{7}$$

where

$$Gr_b^* = \frac{g\alpha_p D^4 q_w}{v_b^2 k_b} \tag{8}$$

It was suggested that the DHT due to buoyancy is expected to take place when $5.67 \times 10^{-7} < B^* < 8.0 \times 10^{-6}$ [10].

Other parameters, Bu^*, k^* and Tanaka ratio, TR, are also used to account for the effect of buoyancy on DHT at a low mass flux condition. The parameters are defined as the following [6, 22–24]:

$$Bu^* = \frac{\overline{Gr_b^*}}{Re_b^{2.7}\overline{Pr_b}^{0.50}} \tag{9}$$

$$k^* = \left(1 - \frac{\rho_w}{\rho_b}\right)\frac{\overline{Gr_b}^{2.0}}{v_{b^2}} \tag{10}$$

$$\mathrm{TR} = Re_f/Re_{fc} \tag{11}$$

where

$$\overline{Gr_b} = g\left(1 - \frac{\rho_w}{\rho_b}\right)\frac{D^3}{{v_b}^2} \tag{12}$$

$$Re_{fc} = 50 \times Gr_f^{\frac{8}{21}} \tag{13}$$

$$Gr_f = \frac{g\alpha_p(T_f - T_b)D^3}{{v_f}^2} \tag{14}$$

T_f, the mean film temperature, is evaluated at $T_f = \frac{1}{2}(T_w + T_b)$.

The occurrence of buoyancy induced DHT will be observed if $Bu^* > 1.0 \times 10^{-5}$ [22], $0.01 < k^* < 0.40$ [6] and [23] or $TR < 1.05$ [24].

The acceleration parameter, A^*, is considered to be responsible for DHT due to acceleration at a low mass flux condition and was found playing an important role for very small diameter tubes [17]. The parameter, A^*, can be formulated as follows [10]:

$$A^* = \left(\frac{v}{u_\infty^2}\right)\frac{du_\infty}{dx} = A_p^* + A_t^* \quad (15)$$

where the compressible acceleration parameter, A_p^* is defined as

$$A_p^* = -\left(\frac{D}{Re}\right)\beta_T \frac{dp}{dx} \quad (16)$$

and the thermal acceleration parameter, A_t^* is defined as

$$A_t^* = \frac{4\alpha_p D q_w}{\mu_b c_p Re^2} \quad (17)$$

Mikielewicz et al. [10] suggested that DHT due to acceleration at a low mass flux condition will be observed when $A^* > 3 \times 10^{-6}$. The acceleration parameter, A^* or any one of the buoyancy parameters, B^*, Bu^*, k^* and TR or both of the acceleration and buoyancy parameters can be responsible for the DHT at a low mass flux condition. It is also expected that any one of the above mentioned parameters will not be able to predict the DHT at a high mass flux condition.

The pressure drops due to different factors, which are used in the present study to analyze and differentiate the DHT phenomenon at low and high mass flux conditions, are derived based on Eq. (8) under steady state conditions as follows:

$$-\frac{dp}{dz} = \frac{1}{A}\frac{d}{dz}(\rho A u^2) + \frac{\tau_w P_w}{A} + \rho g \quad (18)$$

$$-\frac{dp}{dz} = \left(\frac{dp}{dz}\right)_{acc} + \left(\frac{dp}{dz}\right)_{fric} + \left(\frac{dp}{dz}\right)_{grav} \quad (19)$$

where $\left(\frac{dp}{dz}\right)_{acc} = \frac{1}{A}\frac{d}{dz}(\rho A u^2)$, $\left(\frac{dp}{dz}\right)_{fric} = \frac{\tau_w P_w}{A}$ and $\left(\frac{dp}{dz}\right)_{grav} = \rho g$.

III. Results and Discussions

Four different experimental cases are selected for the simulations carried out in this paper. The details of the experimental parameters are presented in Table 1. The q_{dht} given in Table 1 is calculated by the following equation [21].

$$q_{dht} = -58.97 + 0.745G \quad (20)$$

TABLE I. Geometrical and Operating Parameters of Experiments

Case #	D (mm)	L (m)	T_{in} (°C)	p (MPa)	G (kg/m²s)	q (kW/m²)	q_{dht} (kW/m²)
1	10	4	350	24.1	1503	590	1061
2a	10	4	350	24.1	203	129	93
2b	25.4	2.79[a]	200	25	380	400	224
3	3	1	120	25.5	1500	1810	1058

a. Unheated bottom length: 0.63 m, heated intermediate length: 2 m, unheated top length: 0.16 m

Case 1 represents the NHT situation whereas Cases 2a and 2b represent DHT at a low mass flux condition and Case 3 shows the DHT at a high mass flux condition. The experiments under consideration dealt with supercritical water flowing vertically upwards in bare circular tubes subjected to constant and uniform heat flux in the periphery. The experimental datasets selected in this study have broad range of operating conditions in terms of mass flux, heat flux, inlet temperature and operating pressure. The validations of THRUST with the above mentioned experimental data were carried out by Dutta et al. [18] and a satisfactory agreement with the experimental results was reported.

A. Analysis of DHT based on the Acceleration Parameters

The acceleration parameter, in fact, is found to be of lower value than the required magnitude for DHT to occur in all the four cases considered in the present study.

The results for all four cases indicate that O $[A_p^*] \sim 10^{-8} - 10^{-9}$ and O $[A_p^*] \sim 10^{-11} - 10^{-12}$. Since, $A^* = A_t^* + A_p^*$ and $A_p^* \ll A_t^*$, $A^* \cong A_t^*$ for all cases under the given conditions. So, A^* is much below the threshold value of 3×10^{-6} for DHT to occur. Thus, it does not affect the DHT. It is noticed that a low value of the compressible acceleration parameter, A_p^* , is obtained even the compressibility effect of supercritical water is accounted for in THRUST.

B. Prediction of DHT based on the Buoyancy Parameters and Pressure Drop Components

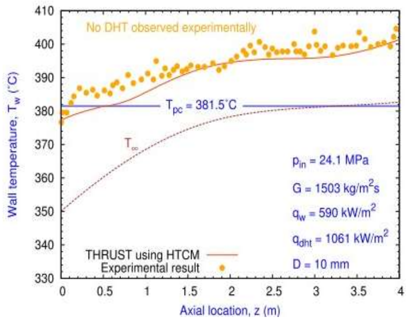
Table 2 provides the summary of the predicted buoyancy parameters using THRUST for all the cases. For Case 1, the maximum B^*, Bu^* and k^* are much lower than the critical values for DHT to occur, and the minimum TR is higher than the critical value. So, there is no DHT for Case 1, which agrees with the experimental observation. For Cases 2a and 2b, the maximum B^*, Bu^* and k^* are higher than the critical values and minimum TR is lower than the critical value. So, DHT occurs in the channel, which also agrees with the experimental observations. However, the predicted buoyancy parameters for Case 3 indicate there is no DHT, but, DHT was observed in the experiment.

1) No DHT in the Experiment

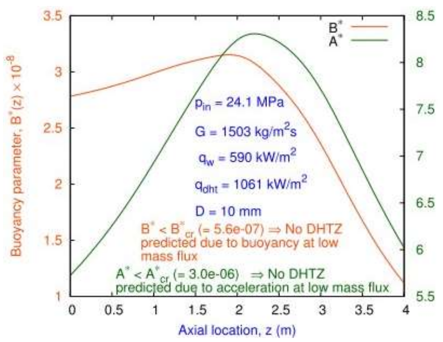
Case 1 where no DHT was observed in the experiment is considered first. Figs. 1b-1d for Case 1 show that all the buoyancy parameters, B^*, Bu^*, k^* and TR, evaluated along the axial direction do not meet the respective criteria required for the onset of DHT. Flow acceleration induced DHT is also out of possibility for the given condition as already discussed in the previous section. Therefore, the numerical predictions indicate that there is no DHT throughout the channel, which is the case as observed based on the wall temperature as shown in Fig. 1a. One important observation from Fig. 1e is that the gravitational and frictional pressure drops across the channel are of comparable values, though the former is dominant initially and it is reversed later on, whereas the acceleration pressure drop across the channel is always less than the other two components.

TABLE II. Prediction of DHT on the Basis of Buoyancy Parameters

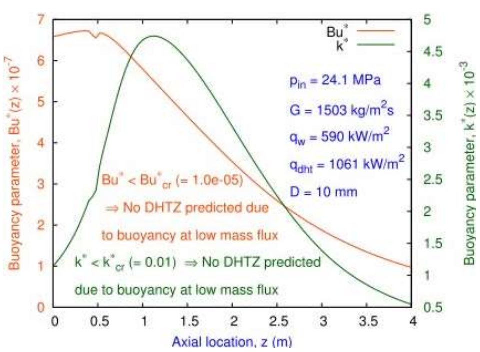
Case #	G ($\frac{kg}{m^2 s}$)	q ($\frac{kW}{m^2}$)	Extreme Axial Value of the Ratio of Buoyancy Parameters			
			$\frac{B^*_{Max}}{B^*_{cr}}$	$\frac{Bu^*_{Max}}{Bu^*_{cr}}$	$\frac{k^*_{Max}}{k^*_{cr}}$	$\frac{TR_{min}}{TR_{cr}}$
1	1503	590	0.06	0.07	0.47	2.52
2a	203	129	11.7	24.9	42.6	0.26
2b	380	400	5.94	14.0	19.1	0.69
3	1500	1810	0.08	0.38	0.68	1.18



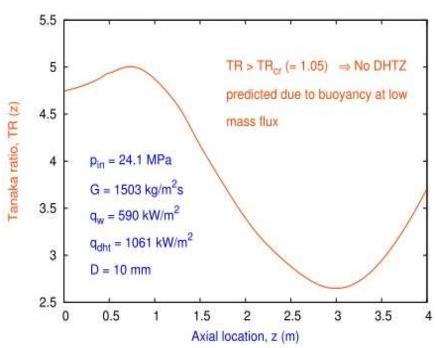
(a) Wall temperature



(b) Buoyancy (B*) and acceleration (A*) parameters



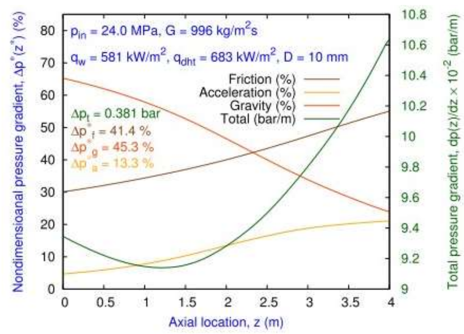
(c) Buoyancy parameters (Bu* and k*)



(d) Buoyancy parameter (TR)

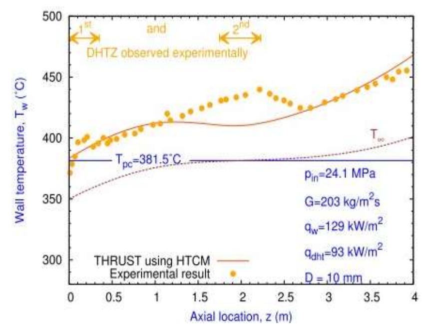
2) DHT Observed in the Experiment at a Low Mass Flux Condition

One can observe from Fig. 2a, the occurrence of DHT in the experiment for Case 2a in the section close to the channel inlet and the middle section of the channel. In those sections, the buoyancy parameter, B*, is found to exceed its threshold limit for the DHT as shown in the Fig. 2b. The similar trends are also observed for other buoyancy parameters Bu*, k* and TR (not shown). However, the DHTZs predicted by the buoyancy parameters are longer than the experimental ones. Therefore, it can be concluded that the numerical models provide a conservative estimate of the DHTZ for this case. The DHTZ was observed for Case 2b experimentally almost everywhere in the channel except around $z* = 0.075$ as shown in Fig. 3a. However, the DHTZ predicted by A* and B* is in the entire channel, as shown in Fig. 3b. The strong dominance of the gravitational pressure drops over the others is observed in Fig. 3c.

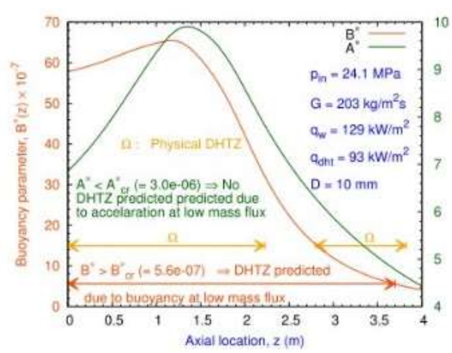


(e) Pressure gradients

Figure 1. Results using THRUST for Case 1

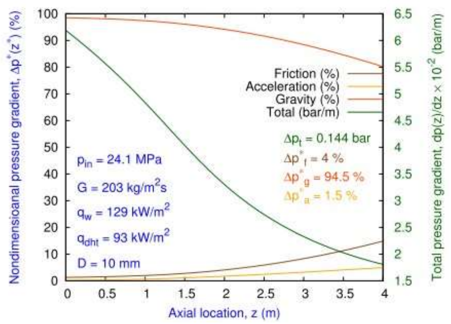


(a) Wall temperature



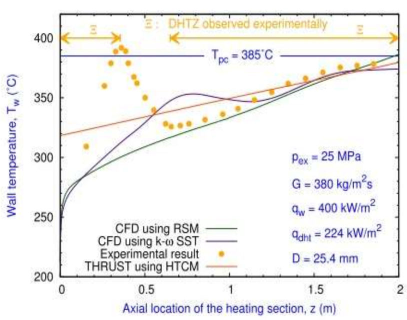
(b) Buoyancy and acceleration parameters

For the Case 3 where the high mass flux condition prevails, it is evident from Table 2 and Fig. 4b, that none of the buoyancy parameter can predict DHT phenomenon inside the channel, though it was experimentally observed as evident in the Fig. 4a. On the other hand it is also observed that the frictional pressure drop is always higher than the gravity and accelerating pressure drops for the Case 3 as shown in Fig. 4c and thus, justifies the negligible effect of the buoyancy for the occurrence of DHT at those conditions.

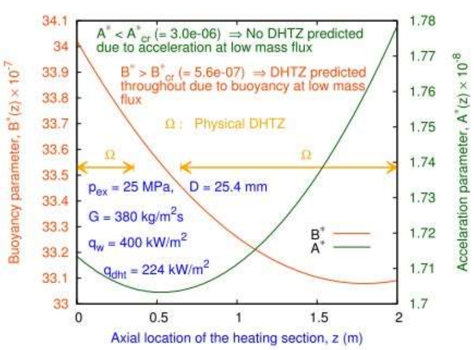


(c) Pressure gradients

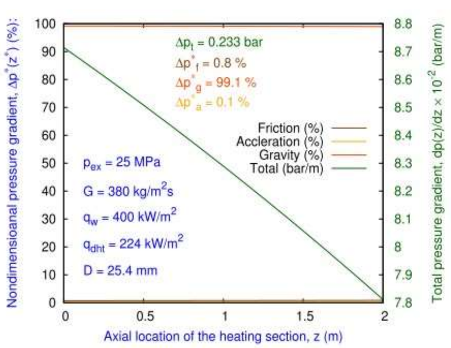
Figure 2. Results using THRUST for Case 2a



(a) Wall temperature



(b) Buoyancy and acceleration parameters

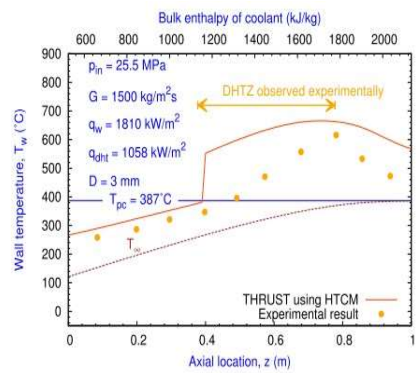


(c) Pressure gradients

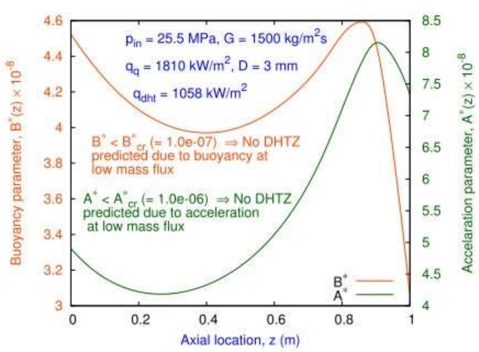
Figure 3. Results using THRUST for Case 2b

3) DHT in the Experiment at a High Mass Flux Condition

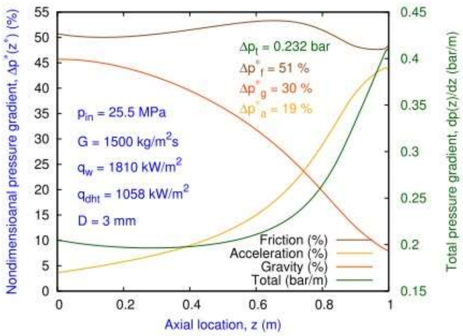
Acceleration pressure gradient, which is having minimal effect at the inlet region of the channel and keeps on increasing along the channel as expected because of continuous heating of the fluid, overcomes the gravitational pressure gradient in the middle section of the channel. As a matter of fact, the same exit section corresponds to the physical (experimental) DHTZ as observed in Fig. 4a. It is noticed that the similar case was studied by Liu et al. [32] and the importance of acceleration pressure drop was emphasized for the given conditions. However, in comparison to the present study, Liu et al. [32] seems to over emphasize the effect of acceleration pressure gradient which was found to be ranging from 64-98% of total pressure gradient depending on its axial location. The acceleration pressure gradient, for the same case study with the present model, THRUST, varies from 4-45% along the axial direction of the channel. Both the studies establish that the friction and acceleration pressure drops play the dominant role in predicting the DHTZ at the high mass flux condition rather than the gravitational pressure drop.



(a) Wall temperature



(b) Buoyancy and acceleration parameters



(c) Pressure gradients

Figure 4. Results using THRUST for Case 3

IV. CONCLUSIONS

The detailed fluid flow and heat transfer analysis of supercritical water flowing in vertically upward tubes is presented. The dimensionless acceleration and buoyancy parameters are used for predicting the DHT in the flow regime. For the case without the DHT, all the buoyancy parameters, can correctly predict that there is no DHT. For the cases with the DHT is observed at a low mass flux, the predicted DHTZs by the buoyancy parameters, B^*, match well with the experimental results. The strong dominance of gravitational pressure drop over the frictional and acceleration pressure drops confirms that the DHT is induced by the buoyancy. For the case with DHT at a high mass flux condition, none of the buoyancy parameters can predict the occurrence of the DHT because the effect of the gravity becomes secondary in comparison to the pressure drop due to friction. Moreover, the acceleration pressure gradient turns out to be having higher influence than the gravitational pressure drops at the exit section of the channel and contributes dominantly for the rapid rise of total pressure gradient in that portion. Flow acceleration due to both pressure drop and thermal expansion is negligible for all of the cases under consideration.

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