CONVECTION HEAT TRANSFER ANALYSES AND CORRELATION FOR ALKALI LIQUID METALS IN UNIFORMLY HEATED TUBES

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ABSTRACT

Performed are Computational fluid dynamics (CFD) analyses of convection heat transfer of liquid NaK-78 in the uniformly heated tube experiments of Talanov and Ushakov [13] at different inlet Pelect Numbers, Pe. Investigated are the effects of Pe on the Nu thermal development length, from the entrance of the heated tube, and on the fully developed Nu values. The good agreement of the calculated axial distributions of the wall temperature and local Nu with the experimental measurements at inlet Pe = 163 and 796, confirms the soundness of the numerical meshing grid and the choice of the turbulence model in the analyses. A recently developed Nu correlation, based on the experimental data of Talanov and Ushakov [17] for Pe from 80-6,490, agrees within ± 15% with a compiled Nu database for liquid Na, and NaK-44, NaK-56, and NaK-78 alloys in uniformly heated circular tubes of different heated lengths and diameters, at Pe = 10-13,000. Results show that the thermal development length of Nu strongly depends on the inlet Pe, and that a heated length ≥ 25-tube diameter is adequate for the thermal development of Nu to ≤ 5% of its fully developed value.

KEYWORDS: Convection heat transfer, uniformly heated circular tubes, alkali liquid metals of NaK-78 and Na, Nusselt number correlation; CFD analyses; turbulence models

1. INTRODUCTION

Many experiments have investigated convective heat-transfer of alkali liquid metals in uniformly heated circular tubes [1-16]. The experimental data and the developed correlations based on the fully developed Nu data, showed considerable variances of as much as 50%, or even higher (Fig. 1). These variances [2, 8, 10, 12, 15] have been attributed to the effect of the oxide impurities on the contact resistance along the heated wall [1, 7, 10, 11], poor wetting of the wall [1, 10], and the possibility that the reported Nu values are for developing, rather than, fully developed flows [7, 10]. Developing flow increases the local Nu, relative that for thermally developed condition.

Recently, Computational Fluid Aynamics (CFD) analyses by the authors [17] investigated convection heat transfer of liquid NaK-78 (22 wt% sodium, 78 wt% potassium) in the uniformly heated circular tube used in the experiments of Talanov and Ushakov [13]. The experimental fully developed Nu values by Talanov and Ushakov [13], for a wide range of Pe =80-6,490, were correlated, to within ± 10% [17], as:

$$Nu = 5.6 + 0.013\ Pe^{0.863} \quad (1)$$

The CFD Nu values were in close agreement (± 10%) with the experimental data and this correlation. This work examines the applicability of the correlation in Eq. (1) to other alkali liquid metals and alloys, based on an extensive database, compiled of the obtained fully developed Nu values in experiments performed by various investigators. In addition to 155 Nu values for liquid NaK-78 alloy, the database

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includes 367 Nu values for liquid sodium and NaK-44 and NaK-56 alloys, covering a wide range of inlet Pe, from 10-13,000 [1, 4, 6, 9-13]. Another objective of this work is to perform CFD analyses to investigate the effect of the inlet Pe on the thermal development length of Nu, for the setup and test section in the experiments of Talanov and Ushakov [13]. The analyses used the STAR-CCM+ 9.04 commercial code package [18] to simulate liquid NaK-78 flows in the uniformly heated tube length (z/D = 50.3) at inlet Pe = 80, 163, 408, 796, 1,217, 1,770, 3,080, and 5,470.

2. COMPILED Nu DATABASE FOR ALKALI LIQUID METALS

In the 1940's through the 1970's, researchers have performed numerous experiments to investigate convection heat transfer of liquid sodium and NaK alloys in uniformly heated circular tubes. The primary objective was to generate experimental data to develop Nu correlations for designing heat transfer equipment, heat exchangers, and nuclear reactors for space and terrestrial power generation [2, 8, 10, 12, 15, 17]. These experiments, for investigating the thermal-hydraulics of the very low Prandtl number` and opaque liquid metals, are quite challenging. The compiled database of the reported experimental results of fully developed Nu in uniformly heated tubes is comprehensive, including a total of 532 Nu values [1, 4, 6, 9-13]. The compiled data are for a wide range of heated tube diameters and length and Pe values from 10-13,000. For thermally fully developed flows, Nu is constant and independent of the distance from the entrance of the heated tube length, but increases with increasing the inlet Pe (Fig. 1).

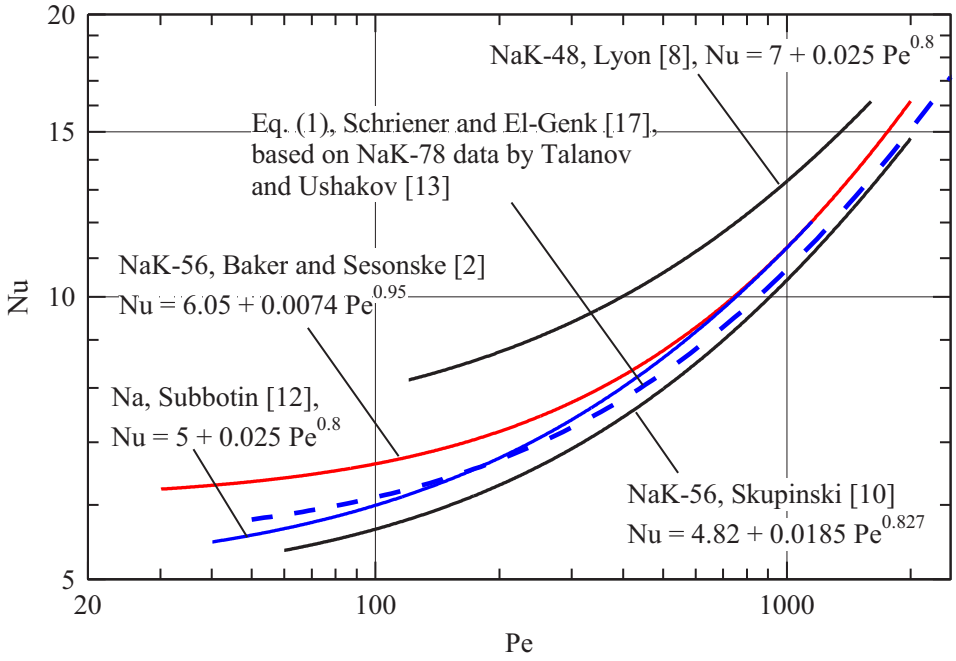

Figure 1. Thermally Fully-Developed Nu Correlations for Alkali Liquid Metals flow in Uniformly Heated Tubes.

The experiments with liquid sodium and alloys of NaK-44, NaK-56, and NaK-78 had used very similar setups, but various tube diameters, heated lengths, and wall materials. They employed either vertical [1, 3-7, 9-13] or horizontal [9-10, 13] tubes heated uniformly using electrical elements. The test sections typically included unheated lengths, for developing the flow, before entering the heated lengths of the tubes. However, in the experiments by Buhr et al. [4] with liquid NaK-78 the velocity of the flow entering the heated tube length was approximately uniform. They determined the bulk fluid temperatures, along the heated tube lengths from the energy balance and the measured inlet and exit temperatures. In addition, they commonly used embedded thermocouples to measure the wall temperature at various axial locations

[3, 5-7, 9-13]. Several experiments used movable thermocouples inside narrow channels or grooves along the heated tube wall for the same purpose [1, 13]. In some experiments, the wall temperatures were also determined by extrapolating the measurements of the radial temperature distributions in the liquid metal flow, using movable immersed thermocouples [4, 11]. In addition, all experiments used cold traps to remove oxide impurities from the flowing liquid metals [1, 10-13].

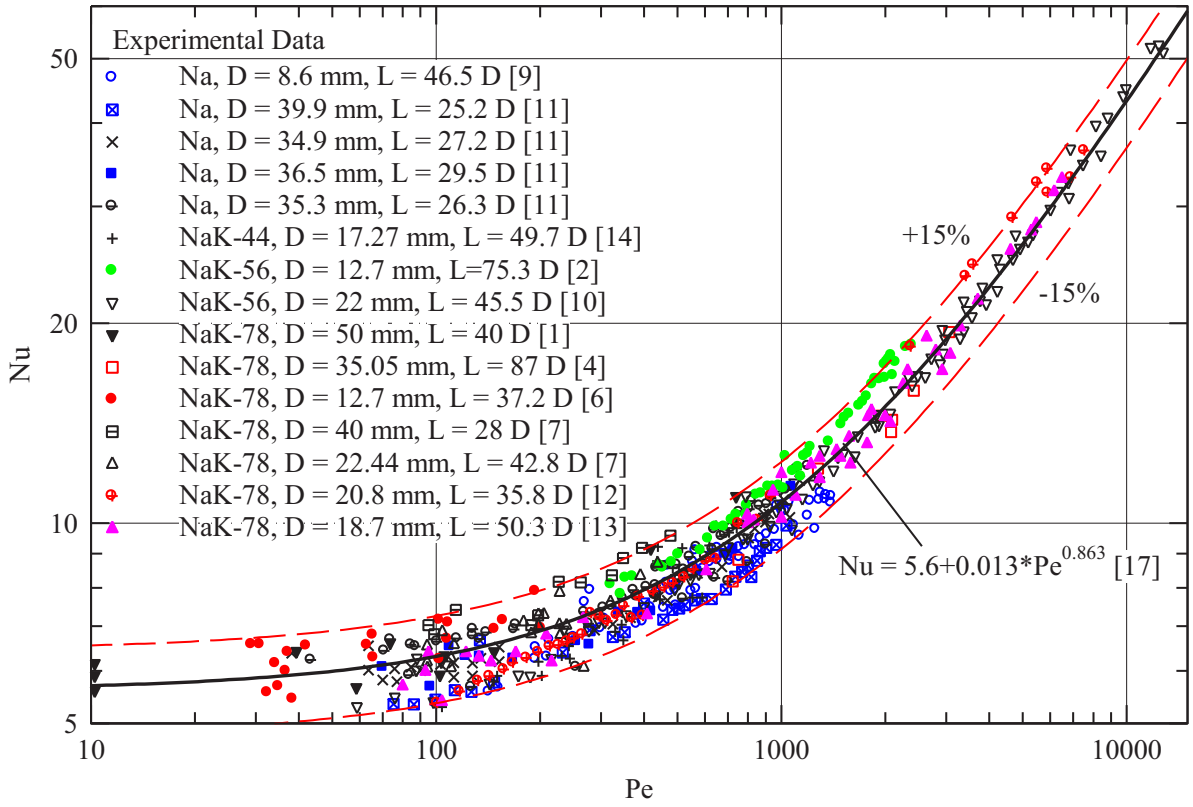

Figure 2. Comparison of Complied Data of Thermally Developed Nu for Alkali Liquid Metals Flow in Uniformly Heated Tubes with Correlation [17].

Other experiments employed a counter-flow annular heat exchanger, referred to as a 'figure eight' in the literature [2, 8, 14]. With the liquid metal counter-current flows in the inner tube and the annular region, heat transfers from one flow to the other. This experimental setup, although encountered in engineering applications, does not represent either an isothermal or an isoflux wall condition. The bulk flow temperatures were measured at the inlet and the exit of the inner tube and the annulus and the wall temperatures were measured using embedded thermocouples [2, 8, 14]. Lyon [8] has reported that, due to failures of the embedded thermocouples along the wall of the inner circular tube, he estimated the wall temperatures of the inner tube by extrapolation from measurements of the annulus outer wall [8]. The error in determining the wall temperature for the inner tube resulted in Nu values [8] that are much higher than those reported by others for uniformly heated tubes (Fig. 1) [2, 10, 12, 17]. Thus, we excluded the reported data by Lyon from the compiled Nu database for uniformly heated tubes, presented in Fig. 2.

This figure compares the compiled fully developed Nu data for flow of liquid sodium (Na) and liquid alloys of NaK-78, NaK-56, and NaK-44 in uniformly heated tubes [1, 2, 4, 6, 7, 9 - 12]. It shows that the recently developed correlation by the authors for liquid NaK-78 [17], based on the experimental data of Talanov and Ushakov [13], agrees well with the compiled database for other alkali liquid metals (Eq. (1)).

The correlation agrees with the majority of the compiled database for alkali liquid metals in uniformly heated tubes [1, 2, 4, 6, 7, 9-12, 14] to within $\pm$ 15%.

The data in Fig. 2 covers a wide range of inlet Pe, from 10-13,000, with the majority of the data is for 100 < Pe < 2,000. The correlation in Eq. (1), shows better agreement, with compiled Nusselt number data for different liquid metals, than the correlations by Lyon ($Nu = 7 + 0.025\ Pe^{0.8}$) [8], Subbotin ($Nu = 5 + 0.025\ Pe^{0.8}$) [12] and others (Fig. 1). The scatter in the experimental data in Fig. 2 at Pe < 200 are likely caused by the small differences between the measured wall and bulk flow temperatures at low wall heat fluxes [1, 5, 6]. Although the reported Nu data in Fig. 2 for liquid Na [9, 11] are consistent with the correlation given by Eq. (1) [17] to within ±15%, most Na data falls below the correlation. Nonetheless, the displayed database in this figure confirms the applicability of Eq. (1) for predicting fully developed Nu for alkali liquid metals.

At the entrance of the heated tube in the experiments, eddy mixing of the flow decreases the difference between the wall and bulk flow temperatures, which increases the local Nu. Thus, the Nu is highest at the entrance of the heated tube length, but decreases exponentially with increasing distance from the entrance. It eventually reaches a constant value as the flow becomes thermally developed and the difference between the wall and bulk flow mixtures is constant. The thermal development length for Nu depends on the heated tube diameter, the inlet Pe, the applied heat flux, and on whether there is an unheated length to develop the flow before entering the heated tube. Therefore, at high inlet Pe, an error in determining the development length and / or using shorter heated tube lengths in the experiments would overestimate Nu values at the exit of the heated tubes.

The performed CFD analyses of convection heat transfer of liquid NaK-78 in the uniformly heated tube in the experiments of Talanov and Ushakov [13], investigated the effect of the inlet Pe on the thermal development length for Nu. This is because, unlike other reported experiments, Talanov and Ushakov provided detailed measurements of the wall temperature and the local Nu along the heated tube length at inlet Pe = 163 and 796. This work used these experimental measurements to benchmark the results of the CFD analyses.

3. CFD ANALYSES AND RESULTS

The performed CFD analyses of the experimental setup of Talanov and Ushakov [Fig. 3] used the STAR-CCM+ 9.04 commercial CFD code [18]. Recent results [17], have shown that the CFD results using the Shear Stress Transport (SST) k-ω and the hybrid SST Detached Eddy Simulation (DES) models are almost identical and slightly closer to the experimental measurements than those using the realizable two-layer k-ε model [17]. The fully developed Nu values calculated using the DES turbulence model differed from those with the k-ω model by less than 1.1%, while those calculated using the k-ε model agreed to within ± 3.7% [17]. However, the computation time using the DES turbulence model was 13 and 14 time that using the k-ω and the k-ε models, respectively [17]. Therefore, the CFD analyses performed in this paper used the SST k-ω turbulence model.

The analyses model the liquid NaK-78 flow in the horizontal test section in Fig. 3, including the heated and unheated tube lengths, but not the heat conduction in the stainless steel tube wall. Neglecting axial heat conduction in the wall is justified on the grounds that the wall is very thin (0.4 mm) and the heated tube length is relatively long (940 mm or z/D = 50.3). The unheated entrance and exit lengths in the test section (Fig. 3) are assumed adiabatic, while the applied uniform heat flux along the heated tube length is the same as in the experiments (41.15 kW/m^2 at Pe = 163 and 116.31 kW/m^2 at Pe = 796) [13].

In the CFD analyses, the liquid NaK-78 properties change with temperature [20] and the liquid flow is considered incompressible, with non-slip at the wall. To account for the high thermal diffusivity and the

low momentum diffusivity of liquid NaK-78 [21-24], Reynolds' equation [24] is used to determine the used values of Pr_t for the liquid metal flows in the analyses (~1.5-2.2). The analyses used the steady state solver, with initial conditions of a uniform inlet temperature and flow at rest. For implementing the k-ω turbulence model, the analyses used the second order upwind convection scheme, the Durbin Scale limiter realizability scheme that constrains the time variable, and the all-y^+ wall treatment options.

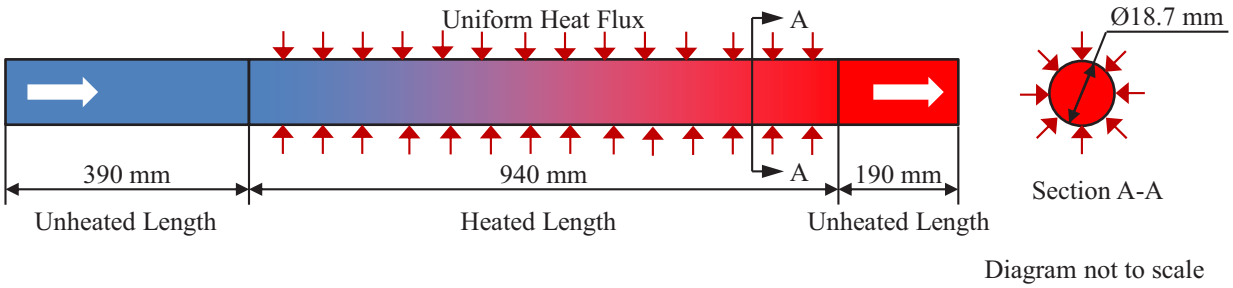

Figure 3. Test Section in the Experiments of Talanov and Ushakov [13].

The bulk flow of NaK-78 in the test section (Fig. 3), including the heated and unheated lengths, is meshed using hexahedral mesh elements (Fig. 4). These elements have a base size of 0.33 mm and an average volume of 0.0359 mm^3. In addition, parallel and exponentially refined prismatic layers are used to mesh the flow region at the tube wall. This, 0.2 mm-thick region contains twelve prism layers whose thickness increases, exponentially by a factor of 1.2, with distance from the wall. Fig. 4 presents a radial cross-sectional view of the 18.7 mm diameter circular tube in the experiments, which shows the developed volume mesh grid used in the CFD analyses. This grid includes 5.1×10^6 mesh elements in the unheated entrance tube length, 13.05×10^6 elements in the heated length, and 2.5×10^6 elements in the exit unheated length [13, 17]. In the analyses with inlet Pe = 796, the values of the wall y^+ along the heated length ranges from 0.95-1.16. This range decreases to 0.265-0.330 in the analyses with the lower Pe = 163.

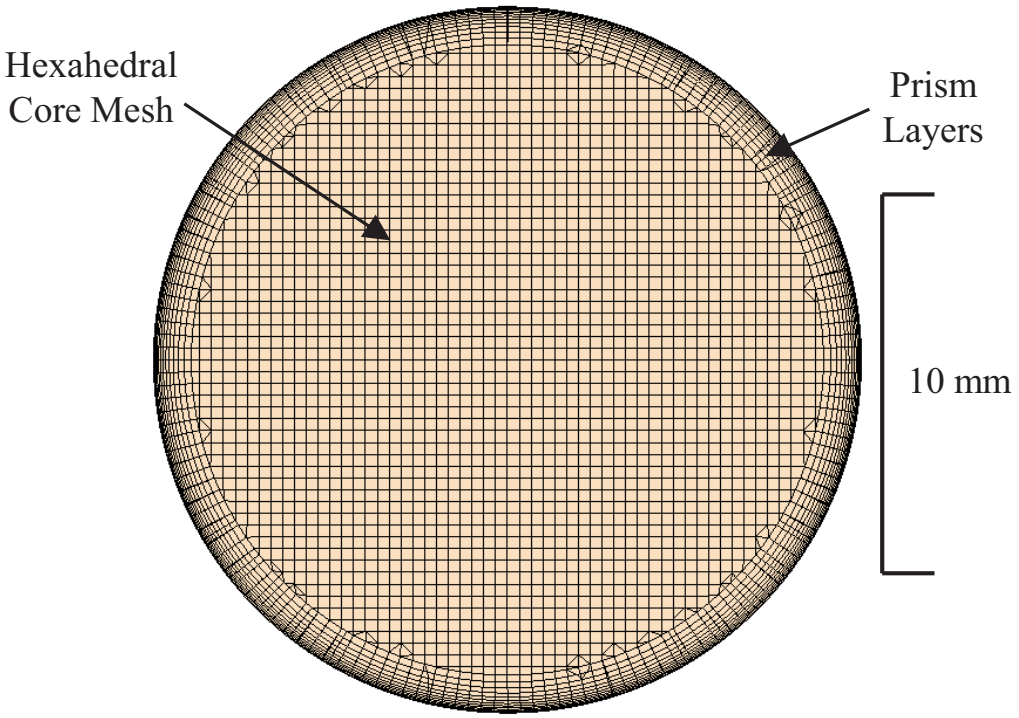

Figure 4. Cross Sectional Views of the Numerical Meshing Grid used in the CFD Analyses of the Test Section in Fig. 3.

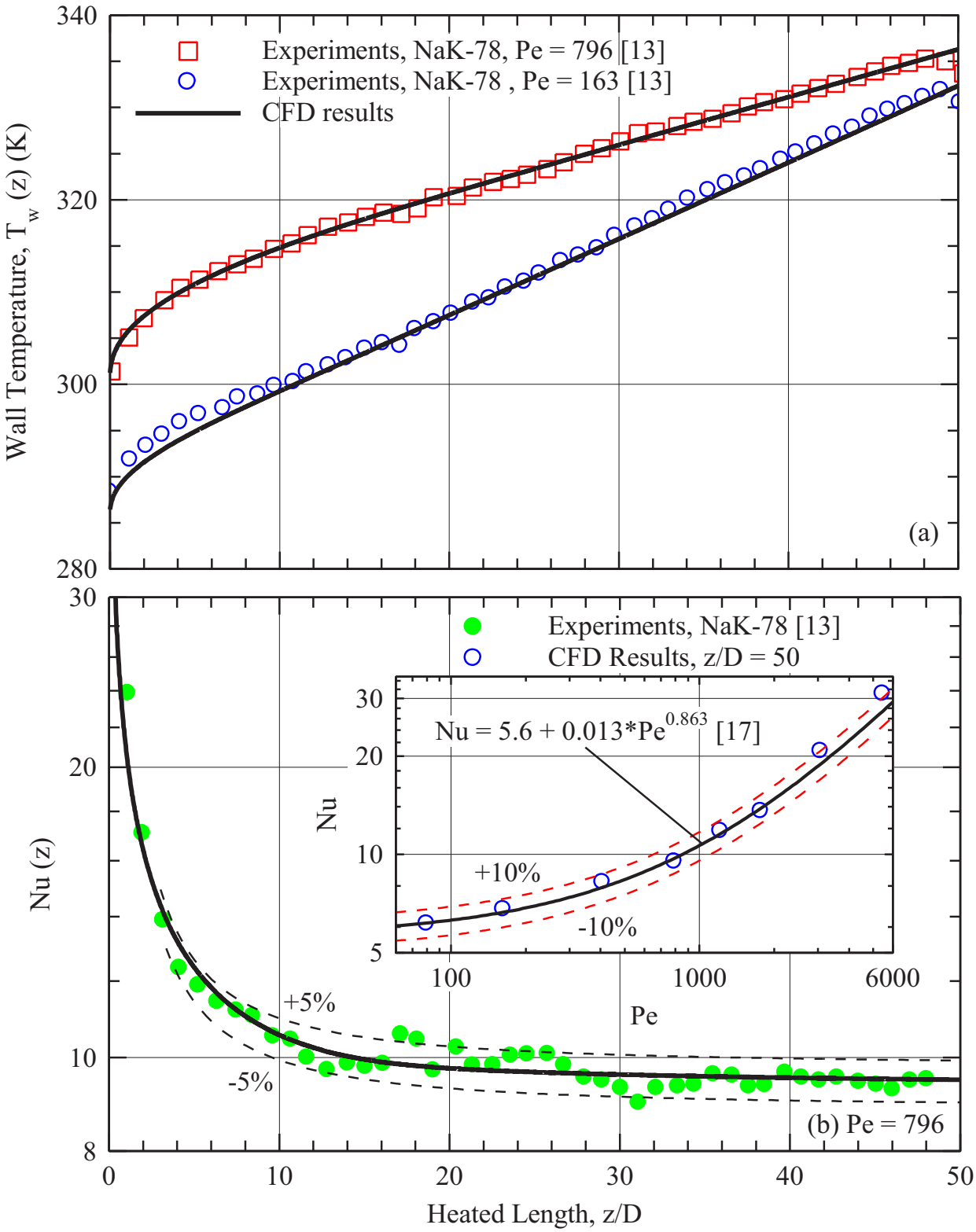

Figure 5. Comparison of Calculated and Experimental Results for NaK- 78 Flow in the Heated Tube Length of Test Section in Fig. 3: (a) Axial Wall Temperatures (a), and (b) Local Nu

3.1. Comparison of CFD Analyses Results with Experimental Measurements

The calculated wall temperatures and local Nu values along the heated tube length (Fig. 3) are compared with the reported experimental measurements (Figs. 5a and 5b). At Pe = 796, the calculated wall temperatures are in excellent agreement with the measurements, to within $\pm$ 0.4 K, and to within $\pm$ 1.0 K at Pe = 163 (Fig. 5a). The largest differences are along the heated length up to $z/D \leq 10$ from the entrance. In the reminder of the heated length, the differences between the calculated and measured wall temperatures in the experiment are negligibly small.

Fig. 5b compares the local Nu values, based on the temperature measurements in the experiment [13], to those calculated at Pe = 796 based on the results of the CFD analyses. At the entrance of the heated tube length, the difference between the tube wall and bulk flow temperatures is small, and which explains the highest local Nu at the entrance (Fig. 3). At $z/D \geq 30$, the numerical and experimental Nu values are lower and approaches those for a thermally developed condition. The calculated local Nu, along the heated tube length agrees with the experimental values [13] to within ± 5%. The insert in Fig. 5b shows that the calculated values of the thermally developed Nu at the end of the heated tube length ($z/D = 50$) for $Pe \leq$ 1,770 agree, within ± 5%, with the correlation in Eq. (1) [17]. The Nu values for higher Pe up to 5,470 agree with this correlation within ± 10%. These good agreements confirm the soundness of the analysis methodology and the numerical meshing grid used in the present CFD analyses.

The reported Nu values in the experiments [13] are from 58 runs, covering a wide range of Pe, from 80 to 6,490. The results of the CFD analyses, presented in Figs. 5a and 5b, for Pe = 80, 163, 408, 796, 1,217, 1,770, 3,080, and 5,470, demonstrate the effect of the increasing the inlet Pe on the thermal development length of Nu in the heated tube length in the experiments [13]. The inlet temperature of the liquid NaK-78 flow into the heated tube length in the experiments was not reported for Pe = 80, 408, 1,217, 1,770, 3,080, and 5,470, so the CFD analyses assumed a value of 300 K.

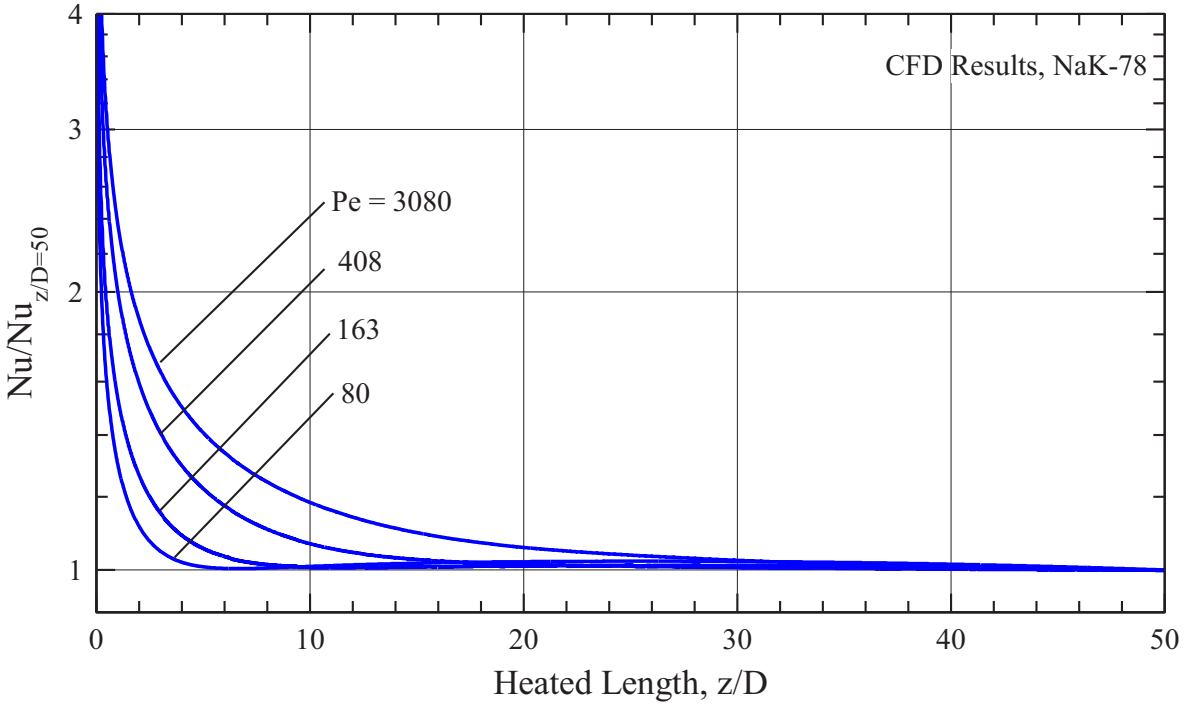

Figure 6. CFD Results of the Local Nu along the Heated Tube Length in the Test Section in Fig. 3, at Different inlet Pe values.

3.2. Developing Nu Results

The thermal development length is where the temperature difference between the wall and the bulk flow, and hence Nu become constant and solely dependent on Pe. Fig. 6 compares the calculated thermal development length of the local Nu, normalized to that near the exit of the heated tube (z/D = 50), for Pe = 80, 163, 408, and 3,080. For inlet Pe = 80, 163, 408, 796, 1,217, 1,770, 3,080, and 5,470, the calculated thermal development lengths of Nu, with different percentages from that at the exit of the heated tube, are compared in Fig. 7. This figure also shows the reported development lengths in the experiments by Ampleyev, et al. [1] and Subbotin, et al. [25] for NaK-78 flows. In all cases, the CFD analyses results confirm that the local Nu at the exit of the heated tube length in the experiments with NaK-78 [13] is practically fully developed.

The local Nu is highest at the entrance of the heated length, decreasing rapidly with increasing distance from the entrance before leveling off at its fully developed values. The Nu thermal development length increases with increasing Pe (Fig. 6). Within two tube diameters from the entrance, the local Nu values at Pe = 80 and 3,080 are 10% and 85% higher than those near the exit of the heated tube length (z/D = 50) (Fig. 6). For Pe = 80 and 163, Nu fully develops within 5 and 10 tube diameters from the entrance of the heated length, respectively. These results demonstrate that the Nu thermal development length strongly depends on the inlet Pe (Fig. 7).

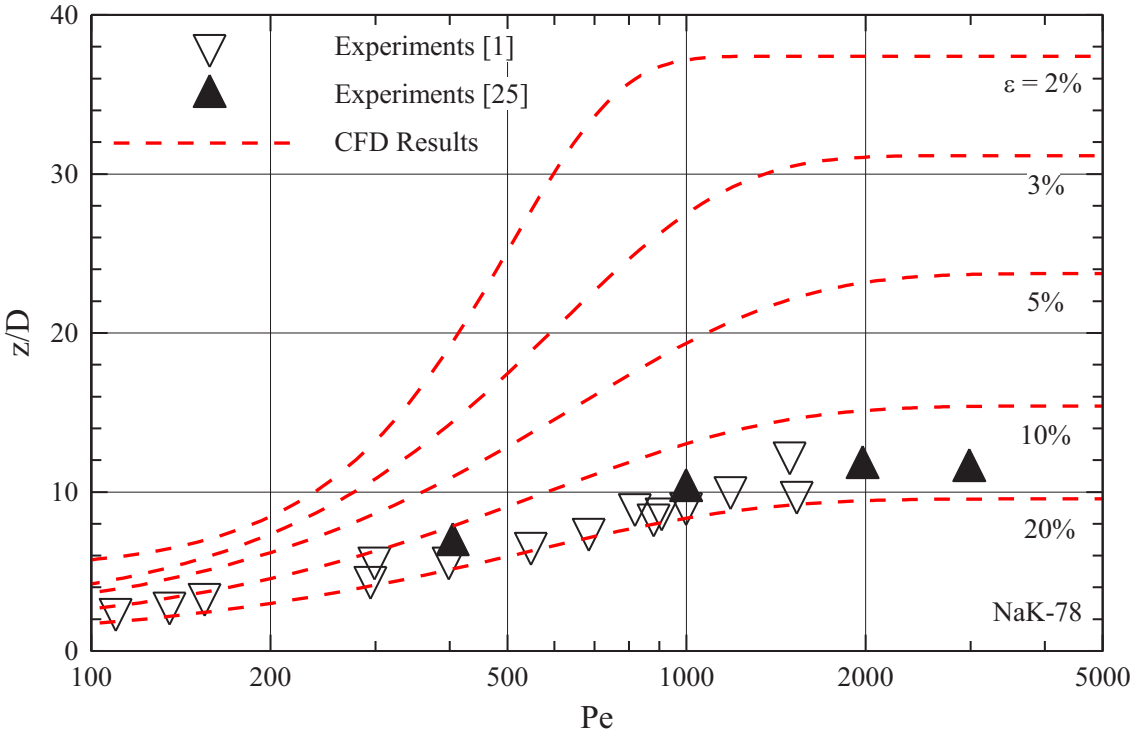

Figure 7. CFD Results of Convergence of Nu Values to that at the End of the Heated Tube Length in the Test Section in Fig. 3.

Results also show that the thermal development length for Nu initially increases with increasing Pe before leveling off to an asymptotic value (Fig. 7). At z/D ≥ 10, Nu develops to within 20% of its value at the end of the heated tube length. The local Nu develops to within 10% and 5% of its value at the end of the heated tube, at z/D ≥ 16 and ≥ 24, respectively. For Nu to develop to within 3% and 2% of its fully

developed value, z/D needs to be ≥ 32 and ≥ 38, respectively. However, for practical consideration a z/D ≥ 25 is adequate for thermally developing Nu for liquid metals in uniformly heated tubes.

The Nu thermal development lengths reported by Ampleyev, et al. [1] at Pe = 110-1,530, are consistent with the experimental results of Subbotin, et al. [25]. However, the heated tube diameter in the experiments by Ampleyev, et al. [1] (50 mm) is larger than in the experiments by Subbotin, et al. [25] (20.8 mm) and by Talanov and Ushakov [13] (18.7 mm). The experiments of Ampleyev, et al. [1] and Subbotin, et al. [25] also used much shorter unheated entrance lengths < 10 D [1, 25]. Despite the longer unheated entrance length in the experiments by Talanov and Ushakov [13] (20.9 D), the CFD results show that the NaK-78 flow entering the heated tube length (Fig. 3) was hydro-dynamically developing. Thus, the liquid metal flows entering the heated tubes in the experiments of Ampleyev, et al. [1] and Subbotin, et al. [25] are expected to be only partially developed. The experimental data in Fig. 7 shows that the reported Nu values by Ampleyev, et al. [1] and Subbotin, et al. [25] are likely within 20% of those for thermally fully developed condition.

4. CONCLUSIONS

The performed CFD analyses of convection heat transfer of liquid NaK-78 flows in a uniformly heated tube investigated the dependence of the Nu thermal development length on the inlet Pe. The compiled Nu data for liquid sodium and sodium-potassium alloys for uniformly heated tubes agree with the correlation in Eq. (1): $Nu = 5.6 + 0.013\ Pe^{0.863}$, to within ± 15%. The CFD analyses are for the test section and conditions in the experiments of Talanov and Ushakov using liquid NaK-78. The analyses results are successfully benchmarked with the reported experimental measurements for the wall temperature and the local Nu along the heated tube length, at Pe = 163 and 796. Performed analyses at Pe = 80, 163, 408, 796, 1,217, 1,770, 3,080, and 5,470 are analyzed for the dependence of the thermal development length for Nu on inlet Pe.

Results show that the Nu thermal development length strongly depends on the inlet Pe number. Within the first 10 tube diameters, local Nu deceases to within 20% of its thermally developed value. Heated lengths ≥ 16 and ≥ 24 tube diameters are adequate for the development of Nu to within 10% and 5% of its thermally developed value. Longer heated lengths of ≥ 32 and ≥ 38 tube diameters are needed for the development of Nu to within 3% and 2% of its thermally developed value. However, for practical consideration a heated length of z/D ≥ 25 is adequate for the thermal development of Nu for liquid metals flow in uniformly heated tubes.

NOMENCLATURE

A_c	Cross sectional flow area (m^2)
C_p	Specific heat capacity (J/kg-K)
CFD	Computational Fluid Dynamics
D	Tube inner diameter (m)
DES	Detached Eddy Simulation
G	Mass flux (kg/m^2-s)
h	Convective heat transfer coefficient (W/m^2-K)
L	Tube heated length (m)
Nu	Nusselt number, hD/λ
$Nu_{z/D=50}$	Nu at the heated length of z/D = 50
Pe	Peclet number, $(GC_p)/(\lambda A_c)$
Pr_t	Turbulent Prandtl number
RANS	Reynolds Averaged Navier Stokes
SST	Shear Stress Transport

T_w	Tube wall temperature (K)
z	Axial coordinate (mm)
ε	$(Nu/Nu_{z/D=50} - 1)x100$
λ	Thermal conductivity (W/m-K)

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