PREDICTION OF WALL FRICTION FOR FLUIDS AT SUPERCRITICAL PRESSURE WITH CFD MODELS

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Abstract

In this paper, the STAR-CCM+ CFD code is used in the attempt to reproduce the values of friction factor observed in experimental data at supercritical pressures at various operating conditions. A short survey of available data and correlations for smooth pipe friction in circular pipes puts the basis for the discussion, reporting observed trends of friction factor in the liquid-like and the gas-like regions and within the transitional region around the pseudo-critical temperature. For smooth pipes, a general decrease of the friction factor in the transitional region is reported, constituting one of the relevant effects to be predicted by the computational fluid-dynamic models.

A limited number of low-Reynolds number models is adopted, making use of refined near-wall discretisations as required by the constraint $y^+ < 1$ at the wall. In particular, the Lien k-ε and the SST k-ω models are considered. The values of the wall shear stress calculated by the code are then post-processed on the basis of bulk fluid properties to obtain the Fanning and then the Darcy-Weisbach friction factors, basing on their classical definitions. The obtained values are compared with those provided by experimental tests and correlations, finding a reasonable qualitative agreement. Expectedly, the agreement is better in the gas-like and liquid-like regions, where fluid property changes are moderate, than in the transitional region, where the trends provided by available correlations are reproduced only in a qualitative way.

1. Introduction

The possibility to make use of fluids at pressure above the critical one in fossil fuelled plants has been matter of study since the mid twentieth century, in the aim to obtain higher thermal efficiency. Presently there are plants in different countries making use of supercritical water with different operating parameters allowing an efficiency up to 45-50% [1].

The possibility to obtain the same advantages in the nuclear field has attracted the attention of various researchers since the sixties. This idea has been recently retrieved leading to the present conceptual design of Supercritical Water Reactors [2-4]. These reactors exhibit several advantages besides the increase of thermal efficiency, including a coolant loop simplification and a corresponding decrease in plant costs. For this reason SCWRs have received so widespread attention in the frame of the studies for Generation IV reactors.

In addition to being used in the energy field, supercritical fluids are adopted in several applications in industry. For instance, they are used also in air conditioning systems and in chemical industry, where they are adopted for selective extraction of components and for waste treatment.

As a consequence, the capability to simulate the behaviour of supercritical fluids is highly desirable and different computational tools are presently updated in order to assess their potential in this regard. In particular, computational fluid-dynamic (CFD) codes make use of balance equations, numerical methods and turbulence models to catch the details of temperature and velocity distributions in different operating conditions. Owing to the general success that CFD codes obtained in the simulation of single-phase fluid phenomena, there are in principle good motivations to hope that a similar success can be obtained with supercritical fluids that, apparently, are just single-phase fluids, involving no presence of interfaces. However, the huge changes in fluid properties that are observed when supercritical fluids cross the threshold of the pseudo-critical temperature are at the root of phenomena that are found difficult to grasp for usual turbulence models, pointing out the need for research and development in this field.

The present work is included in the studies going on at the University of Pisa in relation to the use of CFD codes for the prediction of phenomena of heat transfer and hydraulic resistance occurring with fluids at supercritical pressure. In particular, the University of Pisa is involved in the Coordinated Research Project of IAEA on “Heat Transfer Behaviour and Thermo-hydraulics Codes Testing for SCWRs” and in the recently established European Project on the Thermal-Hydraulic of Innovative Nuclear Systems (THINS), in whose frame it develops different tasks related to heat transfer, hydraulic resistance, stability and natural circulation. The use of CFD codes represents a considerable part of in the tasks to be addressed and, in particular, the assessment of the STAR-CCM+ code [5] is one of the main objectives pursued in THINS.

In this frame, the particular objective of the present work is to compare the hydraulic resistance predicted by the STAR-CCM+ code with applicable experimental data. In this aim, the available literature on the subject has been considered, identifying a few interesting data sets that are used in the work for purpose of comparison.

2. Suggestions obtained from previous literature

A survey of the relevant literature on the subject (see e.g., the textbook by Pioro and Duffey [1]) suggests that frictional pressure drops in supercritical fluids can be evaluated by relationships which are basically similar to those adopted for single-phase subcritical fluids. However, in these conditions it is necessary to introduce corrections taking into account the significant changes of the physical properties across the pseudo-critical temperature. These corrections are among the targets of researches in this field.

The usual Darcy-Weisbach relationship is still adopted for defining the friction factor to be used in evaluating friction losses basing on bulk fluid density and velocity:

$$\Delta P_{fr} = \xi \frac{L}{D} \frac{\rho_b u_b^2}{2} \tag{1}$$

Experimental and analytical approaches are used for determining the friction factor, ξ, appearing in the above relationship, with an obvious preference for experiments. Most of the addressed ducts have a cylindrical geometry with both vertical and horizontal orientation. Fuel bundle tests are also available, though they will not be considered in this work, mainly focused on simple boundary conditions. Water and CO_2 are the most frequently adopted fluids, though Freon refrigerants and Helium have been also tested.

Table 1 and Table 2 report the relevant works mentioned in similar tables of Ref. [1]. Among the relevant conclusions that can be drawn by the analysis of the available studies, the following can be considered:

- most of the experimental work is focused on smooth pipes; therefore, the comparison of the measured friction factors is mainly made with smooth pipe correlations, as the classical Blasius, McAdams or Filonenko ones; it was found that these correlations provide a reasonable description of experimental data in the case of adiabatic pipes (i.e., isothermal flow with no change in properties along the duct);

- in the presence of heat flux at the wall, the ratio of the measured friction factor to the one evaluated by smooth pipe correlations on the basis of bulk properties is generally seen to decrease below unity when the temperature at the wall crosses the pseudo-critical region, while it approaches unity in the liquid-like and gas-like regions; in other words, it seems that classical correlations for friction factors work reasonably well, at least for smooth pipes, in the liquid-like and gas-like regions, limiting the zone of large uncertainties to the one across the pseudocritical threshold, where the fluid undergoes sharp changes in properties;
- the effect of wall temperature in the region across the pseudo-critical threshold is the main target of corrections proposed to the classical friction factor correlations; some of the proposed correlations have the form

$$\xi = \xi_0 \left(\frac{\mu_w}{\mu_b}\right)^a \left(\frac{\rho_w}{\rho_b}\right)^b \tag{2}$$

  where ξ_0 is the friction factor evaluated by the isothermal formulations and a and b are appropriate exponents that may be different for different fluids and enthalpy ranges and for addressing local or pipe averaged conditions (see e.g., Ref. 8). For instance, some of the proposals for the correcting factors are:

$$\begin{array}{ll} 1) & \left[(\mu_w/\mu_b)(\rho_w/\rho_b)\right]^{0.18} \\ 2) & (\rho_w/\rho_b)^{0.4} \\ 3) & (\rho_w/\rho_b)^{0.3} \end{array} \tag{3}$$

  (see e.g., Refs. [6-8]) whose use will be made in the following to compare with calculated data; this link between the wall temperature and the friction factor represents a major challenge for its prediction, since wall temperature is affected by phenomena like heat transfer enhancement and deterioration, whose prediction is rather difficult with both correlations and CFD codes; as it will be shown, this represents one of the serious complications in the present analysis.
- some of the papers are not completely clear in defining boundary conditions or the reference isothermal friction factor correlation, introducing some uncertainty in the use of presented data;
- obtaining experimental data on friction factors with supercritical fluids by a one-dimensional approach appears relatively challenging, since assumptions must be made in data processing about velocity distribution across the channel, e.g. in order to discriminate the contribution of acceleration; this introduces some uncertainty in the interpretation of experimental data;
- in a few cases, the increase of friction due to the presence of roughness was assessed, but the related information is not enough systematic.

3. Methodology of analysis

The analysis of the experimental conditions for which data were considered clear enough to try a prediction was performed by adopting the STAR-CCM+ code obtaining the calculated value of the shear stress at the wall.

Reference	P(MPa)	t(°C)(H in kJ/kg)	q"(MW/m^2)	$G(kg/m^2s)$	Geometry
Vertical pipes					
Tarasova e Leont'ev (1968)	22.6-26.5	$t_b o H_b$ non specificati	0.58-1.32	2000;5000	D=3.34mm, L=0.134m D=8.03mm, L=0.602m
Krasyakova e al. (1973)	23; 25	$H_b = 450 - 2400$	0.2-1	500-3000	D=20mm, L=2.2;7.73m
Chakrygin e al. (1974)	26.5	$t_{in} = 220 - 330$	non specificato	445-1270	D=10mm, L=0.6m
Ishigai e al. (1976)	24.5; 29.5; 39.2	$H_b = 220 - 800$	0.14-1.4	500;1000;1500	D=3.92mm, L=0.63m
Razumovskiy e al. (1985)	23.5	$H_{in} = 1400; 1600; 1800$	0.6557-3.385	2190	D=6.28mm, L=1.44m
Horizontal pipes					
Kondrat'ev (1969)	22.6;24.5;29.4	$t_b = 105 - 504$	0.121.2	$Re = 10^5$	D=10.5mm, L=0.52m
Krasyakova e al. (1973)	23; 25	$t_b o H_b$ non specificati	0.2-1	500-3000	D=20mm, L=2.2;4.2m
Ishigai e al. (1976)	24.5; 29.5; 39.2	$H_b = 220 - 800$	0.14-1.4	500;1000; 1500	D=4.4mm, L=0.87m

Table 1. Characteristics of experiments performed with water (adapted from [1] where a detailed list of references can be found)

Reference	P(MPa)	t(°C)	q"(kW/m^2)	$G(kg/m^2s)$	Geometry
Vertical pipes					
Petukhov e al. (1983)	7.7;8.9	$t_b = 0 - 80$	384-1053	1000;4100	St.St.tube (D=8mm,L=1.67m)
Kurganov e al. (1989)	9	$t_{in} = 33 - 36$	170-440	2100	St.St.tube (D=22.7mm,L=5.2m)
Horizontal pipes					
Kuraeva e Protopopov (1974)	8;10	19-88,t_w fino a 500	fino a 2500	1140-7400	St.st.tube (D=4.1mm,L=0.21m)
Petukhov e al. (1980)	7.5-7.8;8;9	$t_{in} = 18 - 20$	870-1480	3270;4130;5230	St.st.tube (D=8mm, L=1.8m)
Petukhov e al. (1983)	7.7;8.9	$t_{in} = 18 - 20$	384-1053	1000-4100	St.st.tube (D=8mm, L=1.67m)

Table 2. Characteristics of experiments performed with carbon dioxide (adapted from [1] where a detailed list of references can be found)

According to a usual procedure adopted at the University of Pisa for CFD analyses with STAR-CCM+ related to supercritical fluids, the fluid properties were assigned in the code in the form of piecewise cubic spline approximations, obtained by the NIST package [9]. The spatial discretisation was adapted to the particular case, including anyway an adiabatic region at the entrance of the channel, to allow for flow development (Figure 1). Circular pipes were addressed by a two dimensional axial-symmetric domain. Since low-Reynolds number models were used, care was taken that the value of the $y+$ parameter at the wall was less than unity as requested by their application. On the other hand, only smooth pipe conditions were addressed, coherently with the use of the low-Re approach, which is intrinsically incapable to deal with rough walls.

The data obtained by the CFD code were exported and processed by a purposely developed code in order to extract the relevant information on bulk fluid parameters and on friction factor. In particular, the calculated shear stress at the wall is used to define the Darcy-Weisbach friction factor on the basis of the local bulk fluid properties by the relationship:

$$\xi = \frac{\tau_w}{\frac{1}{8}\rho_b u_b^2} \tag{4}$$

where the bulk density and velocity appear at the denominator. In one case, the values of the friction factor were averaged along the pipe (Figure 2) while in all the other cases, local calculated values were reported. The lack of precise information on the inlet conditions adopted for each experimental data point, required to elaborate a procedure to cover the whole range of bulk enthalpy presented in the related plots with the prescribed heat flux and flow rate. The CFD calculations were then performed subdividing the entire bulk enthalpy range into arbitrary intervals and assigning at the pipe inlet in each calculation the values of fluid temperature obtained at the outlet of the pipe in the previous one.

The comparison of the obtained friction factor was therefore made with smooth pipe relationships like the classical Blasius (for Re < 30000) or McAdams ones (for larger values of Re). The relationship by Filonenko was also considered for comparison:

$$\xi = \left(1.82\log_{10}\mathrm{Re}_b - 1.64\right)^{-2} \tag{5}$$

A first check of the response of the code was made considering adiabatic conditions (i.e., without property changes) at both subcritical and supercritical pressure. These analyses served for validating the adopted calculation procedure and for assessing the adequacy of the models adopted in the CFD code for "normal" smooth pipe friction prediction. Table 3 and Table 4 summarise the boundary conditions adopted in these analyses and the obtained results. As it can be noted, the two turbulence models used in these analyses were the "standard" k-ε low-Re model available in the code [10] and the SST k-ω model [11]; the results obtained by the calculations support the adequacy of the adopted procedure and of the adopted models in predicting smooth pipe friction. The discrepancies observed between the obtained results and those proposed by the different correlations clearly highlight also the accuracy limitations of the comparisons presented hereafter.

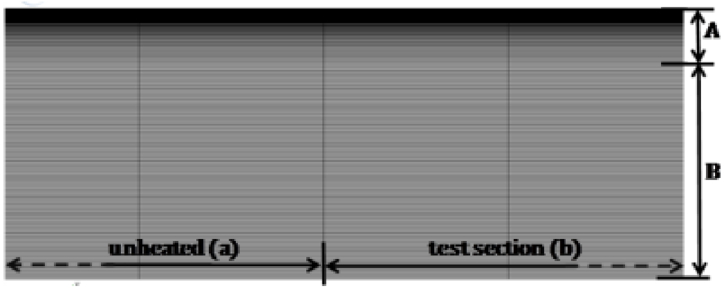

Figure 1. Typical adopted radial discretisation for low-Re number model application

Pressure	D [m]	G [kg/m^2 s]	ρ [kg/m^3]	u [m/s]	μ [Pa · s]	Re
1 bar	0.0044	2100	997	2.1	$8.90 \cdot 10^{-4}$	$1.04 \cdot 10^4$
245 bar	0.0044	1000	587	1.7	$6.78 \cdot 10^{-5}$	$6.5 \cdot 10^4$

Table 3. Boundary conditions adopted for the comparison of friction factors for adiabatic cases at subcritical and supercritical pressures

Pressure	Blasius	McAdams	Filonenko	ξ [LIEN k-ε]		ξ [SST k-ω]	
				vertical	horizontal	vertical	horizontal
1 bar	0.03131			0.03223	0.03223	0.03290	0.03290
245 bar		0.02006	0.01973	0.02137	0.02137	0.02152	0.02152

Table 4. Comparison of friction factors obtained by different correlations for adiabatic cases at subcritical and supercritical pressures

4. Obtained results

A first analysis was performed considering the data by Kondrat'ev (1969) [12], as reported in the textbook by Pioro and Duffey [1], for water in horizontal tubes. The boundary conditions of these tests were chosen within the ranges declared in the reference (bulk temperature from 105 to 540 °C, heating flux from 0.12 to 12 MW/m^2) with a Reynolds number in the order of 10^5. The adopted fluid is water at 25.3 MPa. The computation of the product $\xi \mathrm{Re}^{0.2}$ allows a direct comparison with the constant appearing in the McAdams correlation (0.184) applicable in this range of conditions for smooth pipes. This comparison is presented in Figure 2, showing that the length averaged friction factor evaluated by the code shows a relatively deep decrease in proximity of the pseudo-critical temperature, greater than reported in the data.

Local values of the ratio of the friction factor to the smooth pipe value obtained by the Filonenko correlation were then calculated for the data by Kaji et al. (1978) [13] related to water in horizontal tubes at the pressure of 24.5 MPa, compared also with results for vertical tubes. Figure 3 to Figure 8 report the results obtained in repeated calculations performed representing local tube conditions and also averaged friction factors along the simulated channel lengths; this information is compared with the values of the friction factor ratio calculated by the three property groups suggested in previous literature. As it can be noted, wherever the experimental data available for comparison are clear enough, a qualitative agreement with the values calculated by the CFD code and by correlations is observed, showing the expected decrease in the friction factor ratio when the pseudocritical temperature is reached at the wall. The location at which this decrease occurs is anticipated with respect to the location at which pseudocritical conditions are reached in bulk, coherently with the fact that the temperature at the wall is increasingly larger than in the bulk fluid as a function of the heat flux.

It must be noted that the ratio of the friction factors was directly calculated on the basis of the values of the shear stress provided by the code and of bulk properties, while determining the values of the property groups required also the evaluation of wall temperature as provided by the code itself; so, the comparison of the CFD code results with correlations is made on the basis of the calculated wall temperature. This aspect represents a major point for both predictions and correlation application. In fact, as shown in Figure 9 to Figure 11, the prediction of wall temperature by the adopted standard low-Re k-ε model tends to provide an overestimate of deterioration, suggesting a further aspect to be carefully accounted for in predicting friction.

Additional information on this key aspect is reported in Figure 12 and Figure 13, reporting also the predictions obtained by the SST k-ω model. As it can be noted in Figure 14, the SST k-ω model provides a better description of wall temperature, showing a milder decrease of the friction factor ratio across the pseudocritical temperature.

Finally, Figure 15 and Figure 16 report the prediction of the data by Petukhov et al. (1980) [14], related to CO_2 in horizontal tubes. The addressed conditions are limited to a small range of bulk enthalpy below the pseudocritical point, though the wall temperature exceeds it. In both the considered cases, the calculated shear stress appears lower than the one derived by the correlation attributed to Popov in Kurganov's paper [8], $\xi/\xi_0 = \left(\rho_w/\rho\right)^{0.4}$, when it is applied with both the experimental and the calculated wall temperatures. In this case, the role of temperature is highlighted in Figure 16, reporting the comparison of the experimental and calculated trends.

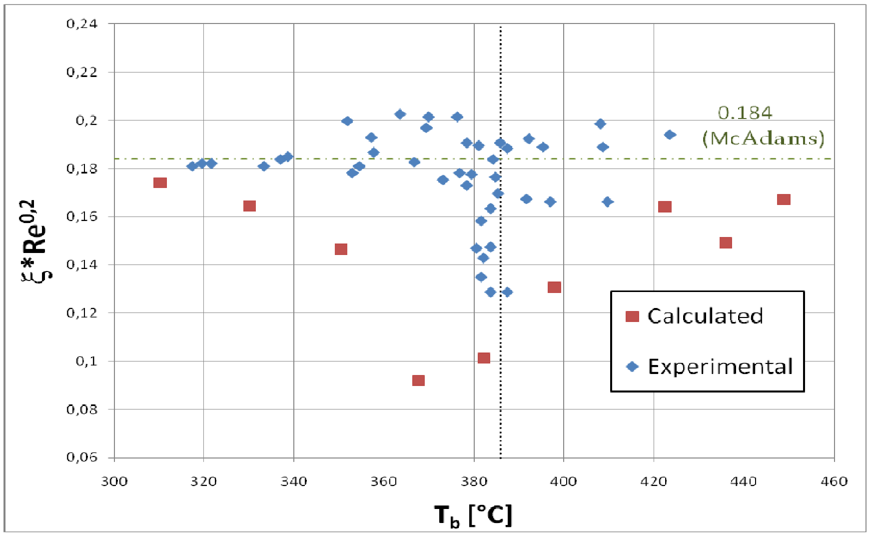

Figure 2. Length averaged value of $\xi\,\mathrm{Re}^{0.2}$ evaluated by the standard low-Re model for Kondrat'ev (1969) data

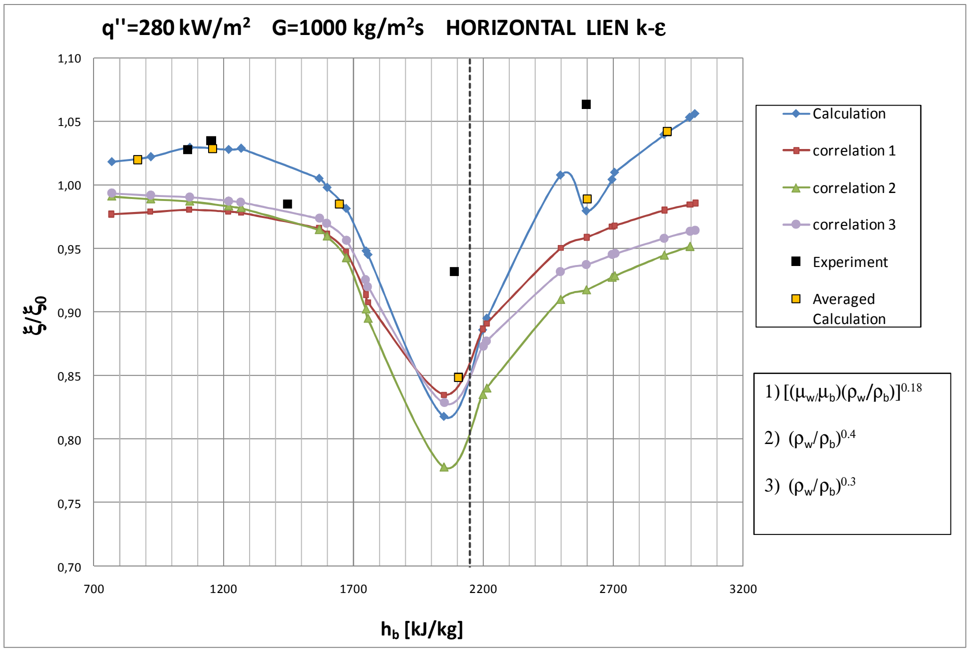

Figure 3. Local friction factor ratio evaluated by the standard low-Re model for horizontal pipe data by Kaji et al. (1978) compared also with correlation trends

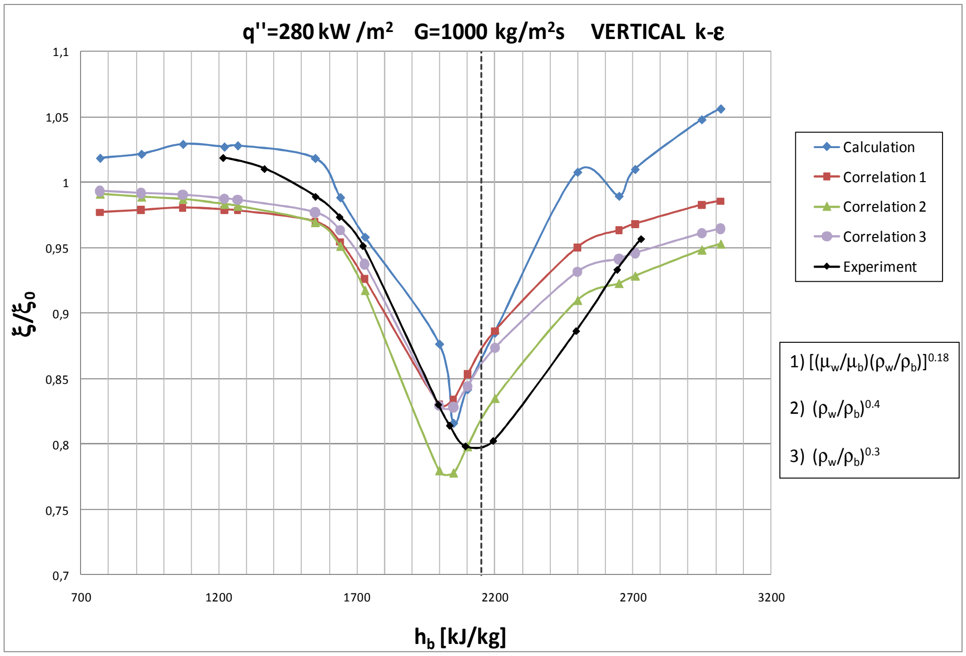

Figure 4. Local friction factor ratio evaluated by the standard low-Re model for vertical pipe data by Kaji et al. (1978) compared also with correlation trends

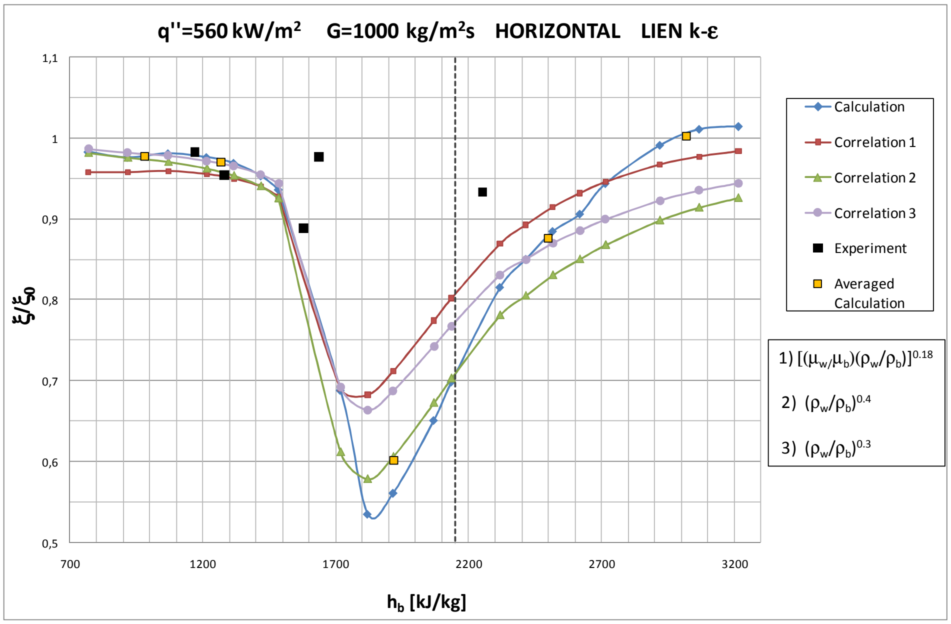

Figure 5. Local friction factor ratio evaluated by the standard low-Re model for horizontal pipe data by Kaji et al. (1978) compared also with correlation trends

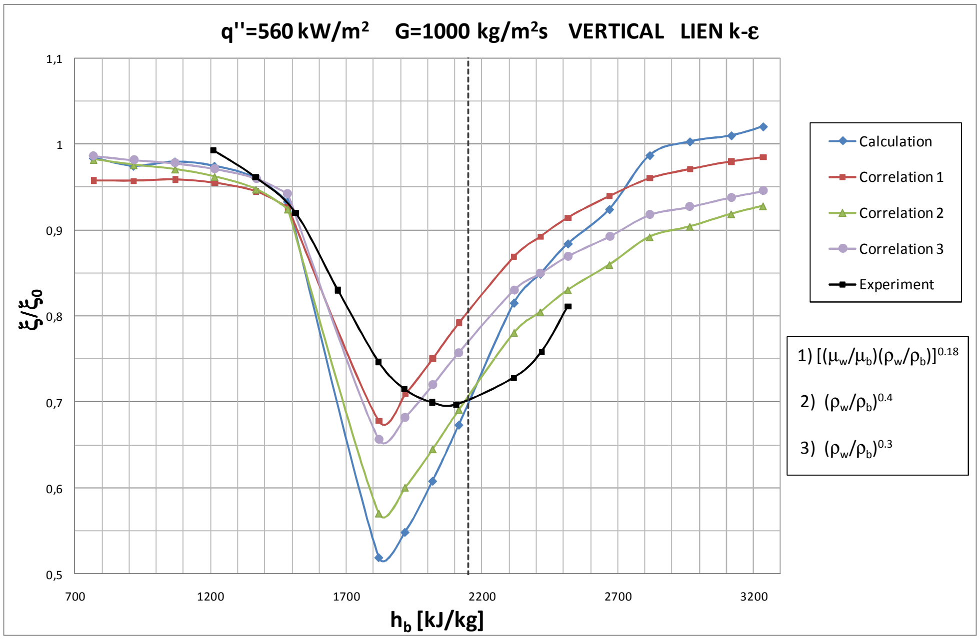

Figure 6. Local friction factor ratio evaluated by the standard low-Re model for vertical pipe data by Kaji et al. (1978) compared also with correlation trends

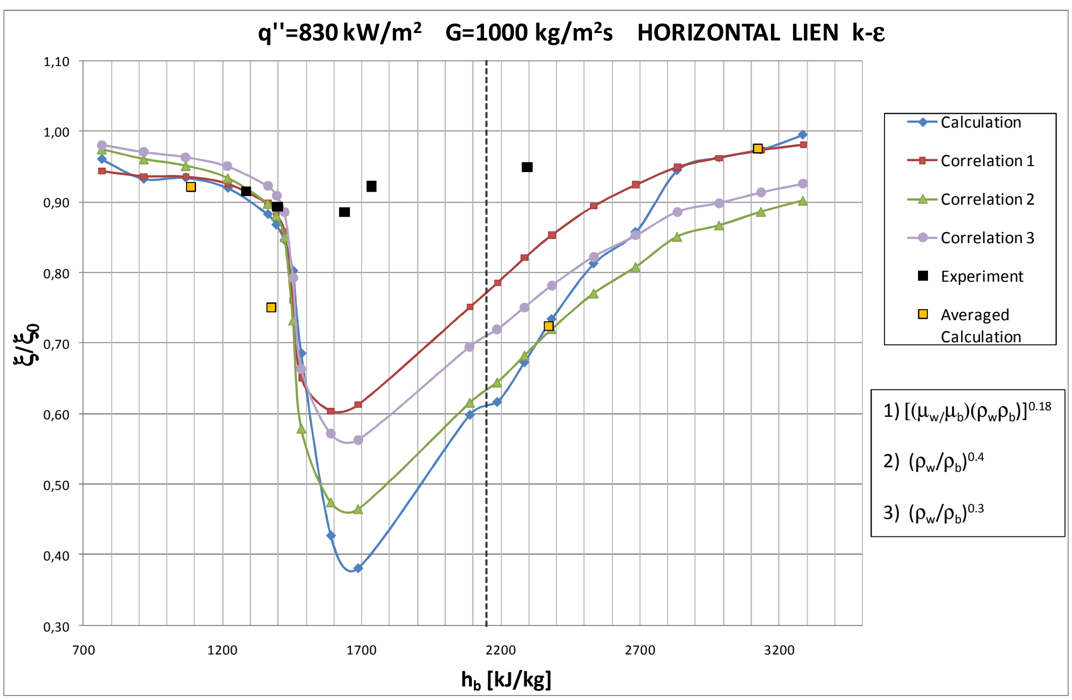

Figure 7. Local friction factor ratio evaluated by the standard low-Re model for horizontal pipe data by Kaji et al. (1978) compared also with correlation trends

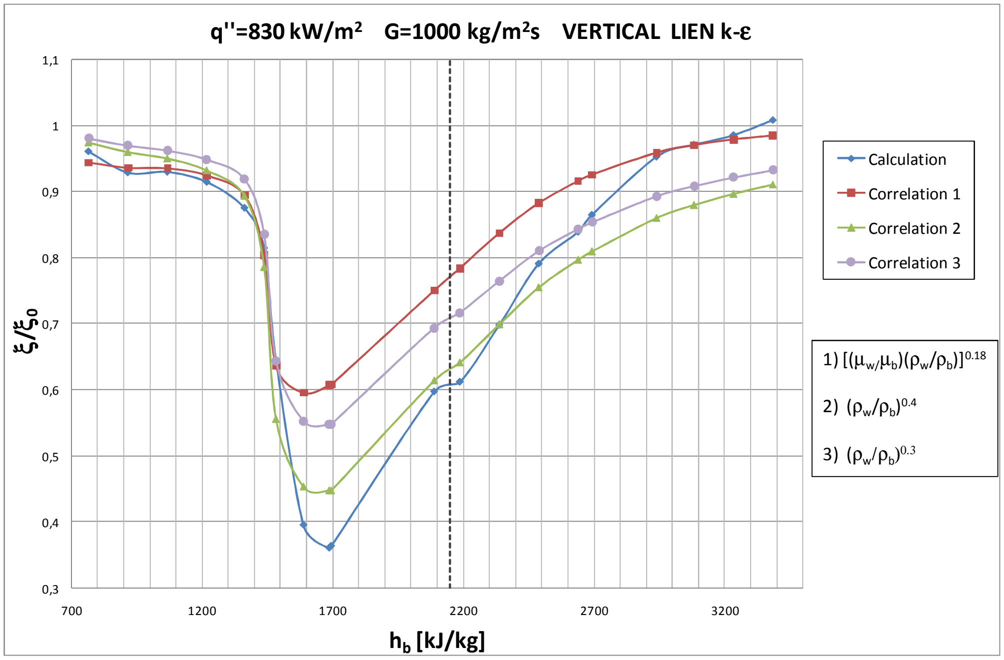

Figure 8. Local friction factor ratio evaluated by the standard low-Re model for vertical pipe data by Kaji et al. (1978) compared also with correlation trends

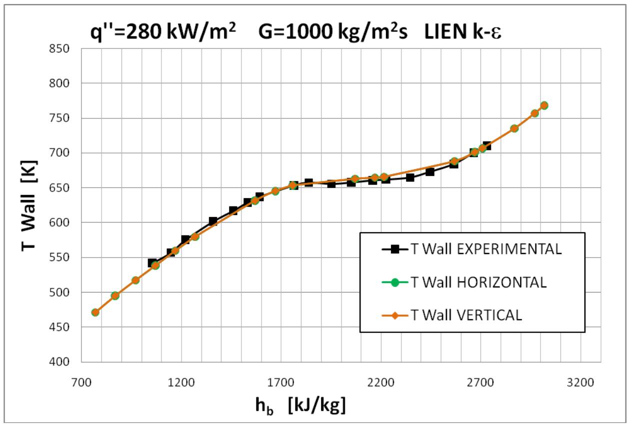

Figure 9. Local wall temperature evaluated by the standard low-Re model for Kaji et al. (1978) data compared with the experimental trends

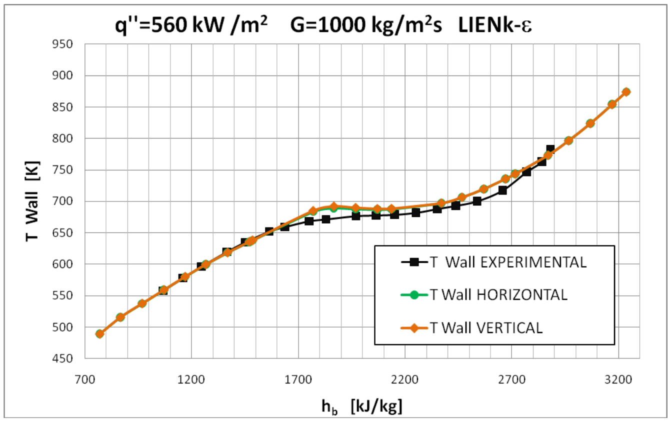

Figure 10. Local wall temperature evaluated by the standard low-Re model for Kaji et al. (1978) data compared with the experimental trends

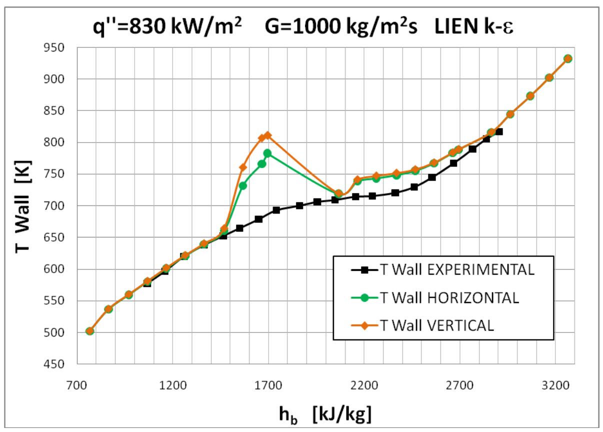

Figure 11. Local wall temperature evaluated by the standard low-Re model for Kaji et al. (1978) data compared with the experimental trends

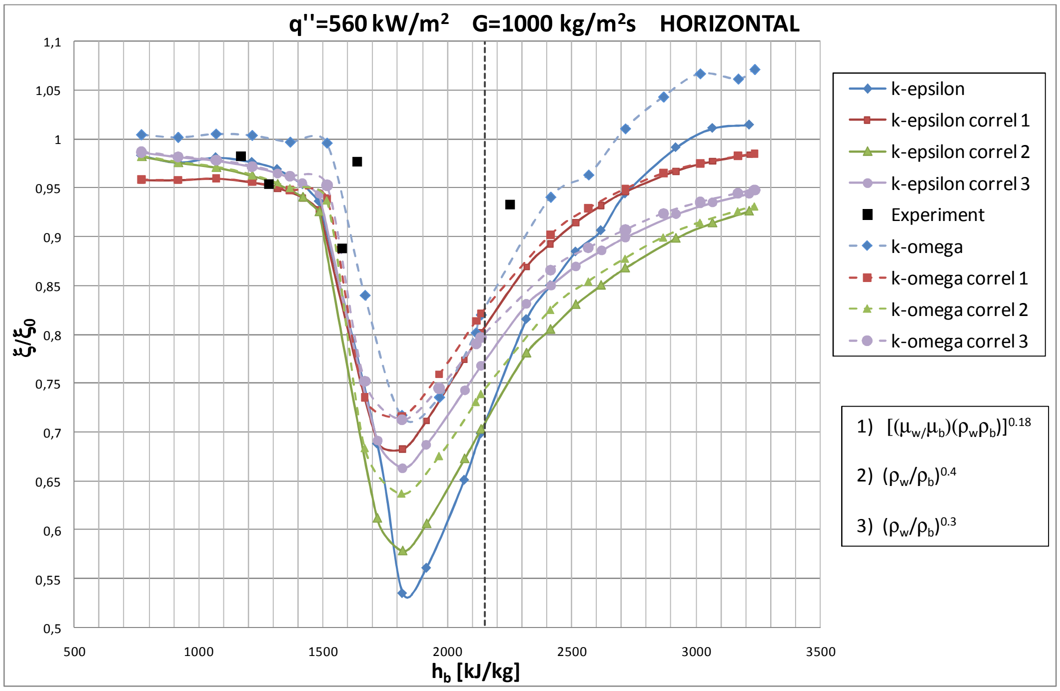

Figure 12. Local friction factor ratio evaluated by the standard low-Re and the SST k-ω models for horizontal pipe data by Kaji et al. (1978) compared also with correlation trends

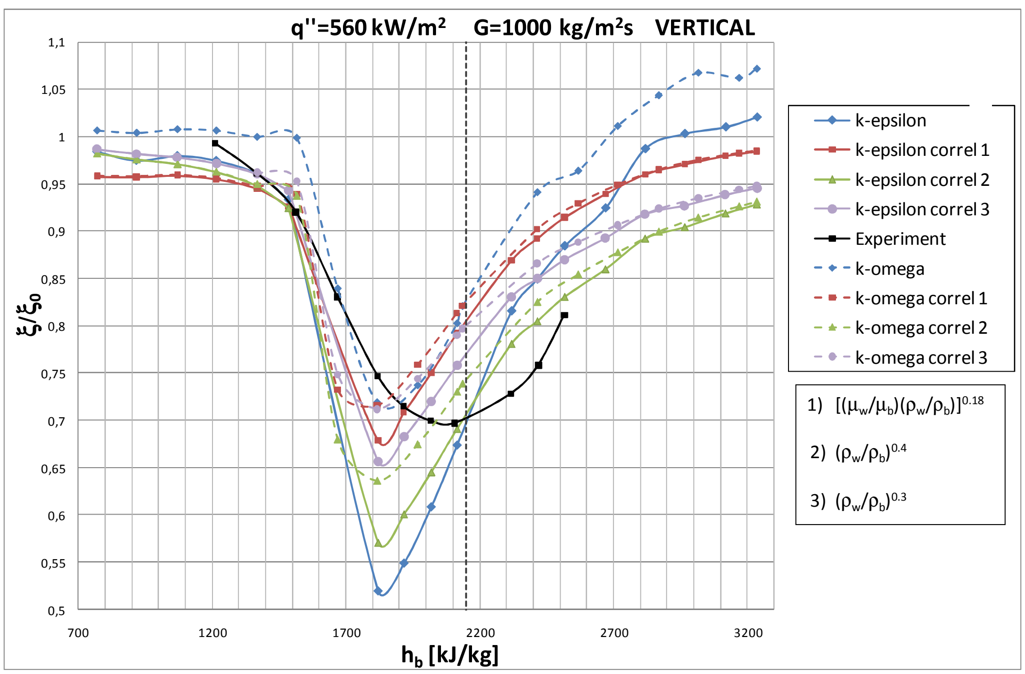

Figure 13. Local friction factor ratio evaluated by the standard low-Re and the SST k-ω models for vertical pipe data by Kaji et al. (1978) compared also with correlation trends

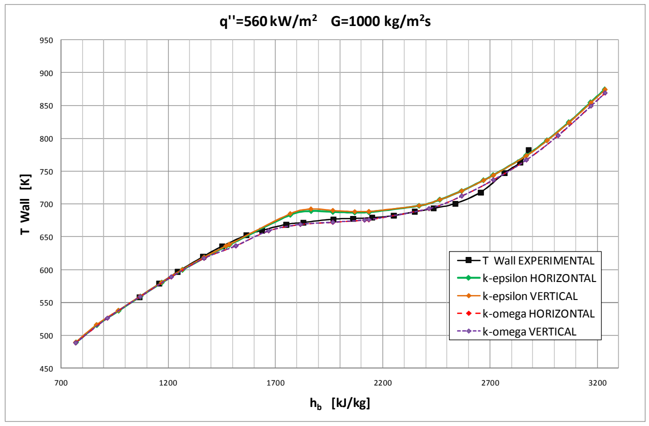

Figure 14. Local wall temperature evaluated by the standard low-Re and the SST k-ω model for Kaji et al. (1978) data compared with the experimental trends

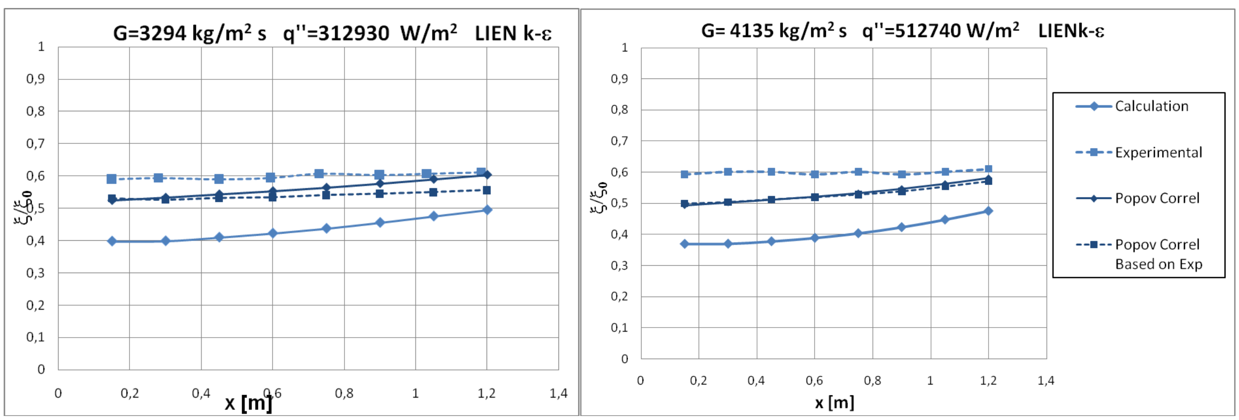

Figure 15. Local friction factor ratio evaluated by the standard low-Re model for data by Petukhov et al. (1980) for horizontal pipes compared also with correlation trends

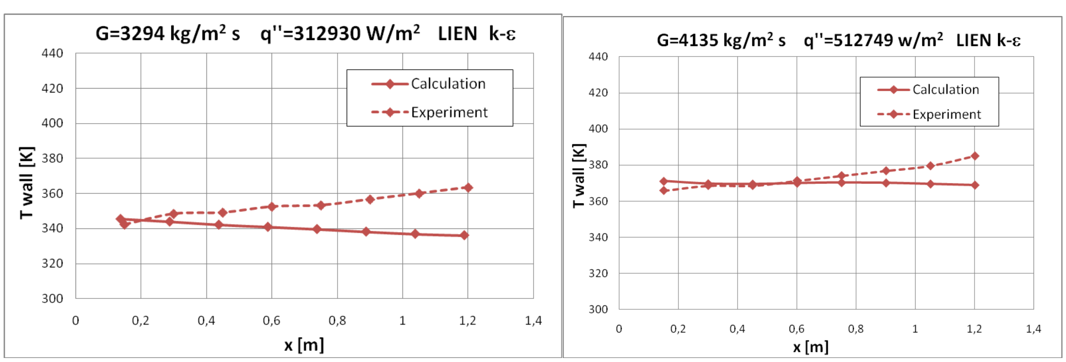

Figure 16. Local wall temperature evaluated by the standard low-Re model for data by Petukhov et al. (1980) for horizontal pipes

5. Conclusions

The results of the performed analyses provide a preliminary overview of the capabilities of the CFD code in predicting the observed hydraulic impedance. The limitations in the performed work are mainly due to the difficulty to obtain well defined boundary conditions for the experimental data reported in literature, which are not always clear enough in the referenced papers.

Despite of these limitations, some interesting aspects were pointed out:

- the general ability of the adopted CFD code in reproducing the observed trend of the friction factor ratio in the liquid-like and gas-like region and when the wall temperature crosses the pseudo-critical value;
- a tendency to overestimate the decrease in the friction ratio across the pseudocritical region at the wall, possibly linked to the prediction of wall temperature.

The latter aspect should be considered with attention. In fact, owing to the present limitations in predicting heat transfer enhancement and deterioration, evaluating friction is relatively challenging for CFD codes, as the two aspects are strictly linked at the level of fluid properties at the wall.

A final mention must be made in relation to the effect of roughness. Though this aspect was not discussed here, because of the scarcity of data, it must be recognised that rough pipe conditions should be addressed in greater detail for a more realistic representation of the hydraulic impedance envisaged to occur in practical applications.

6. References

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