TRANSIENT SIMULATIONS OF UNSTEADY HEAT TRANSFER IN TURBULENT PIPE FLOW

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Unsteady convective heat transfer in pipes is an important feature in a broad range of engineering devices. An improved understanding of the underlying mechanisms would further contribute to the design of such practically important devices as automotive engines and pulse combustors[1]. An enhancement of the effectiveness of heat exchangers through flow unsteadiness has also been suggested[2]. A detailed understanding of the transient convective heat transfer is important not only for the insight it provides to the mean heat transfer problem, but also in its own right, where it might find application, for example, in the design of inlet manifolds in automotive engines[3].

In analysing fluid flow problems, Computational Fluid Dynamics (CFD) based simulation procedures have gained such maturity, within the last decade that they are now considered to be an indispensable analysis and design tool in a wide and ever-increasing range of applications involving fluid flow. The convective heat transfer has also been analysed quite intensively employing computational procedures. Many of the publications in this area are concentrated on the issues concerning the turbulence modelling including second moment closure models[4] and two-equation models with different levels of sophistication[5].

The numerical predictions of flow problems are principally afflicted with errors, mainly due to inaccuracies in the turbulence modelling, as the modelling of near-wall turbulence deserves a particular attention in convective heat transfer. Therefore, the issue of model validation occupies a central role in the computational analysis of flow problems. Validation of computational predictions of the convective heat transfer has also been performed by many authors[6]. However, as it is also the case in a very recent and quite exhaustive investigation[7] on the performance of turbulence models in convective heat transfer, the main emphasis has been lying onto the steady state problems in such validation studies. Validation of computational procedures in predicting the transient convective heat transfer has received comparably less attention. This is scope of the present contribution. The unsteady convective heat transfer in pipe flow will be investigated computationally, using different turbulence models, and the results will be validated by comparisons with experiments.

As the experimental basis, the recent transient convective heat transfer measurements by Barker and Williams[8] will be utilized. In these experiments, the unsteady turbulent pipe flow subject to sinusoidal perturbations at different amplitudes (8% - 80%) and frequencies (0.5 – 30 Hz), as well as non-sinusoidal changes of the mass flow rate were investigated. The Reynolds numbers based on the time average velocity were varying between 8000 and 30000. For sinusoidal perturbations at high amplitudes a temporal relaminarisation and retransition of the flow was also observed. The pipe wall was held at a constant temperature of 80°C. Transient measurements of the velocity, temperature and wall heat flux rate were performed.

For the numerical investigations, the general purpose CFD code Fluent[9] will be used as the basis, which utilizes a finite volume method to discretize the governing equations and a pressure-correction formulation to handle the velocity-pressure coupling. Higher order discretization schemes will be used for spatial and temporal discretisation, for attaining a high numerical accuracy. Grid independency of the results will be assured. Since the second moment closure turbulence models are not necessarily indicated by the comparably less complicated fluid dynamics of the pipe flow, and since we primarily aim to validate models, which do not necessarily imply a very high computational overhead, the attention will be focussed, in the present study, on the validation of two-equation turbulent viscosity models, including standard k-ε [10], RNG k-ε [11,12], and k-ω [13] models. The modelling of the near-wall region is especially important in convective heat transfer problems. Several formulations including standard[10] or non-equilibrium[14] wall-functions (overbridging this region adopting wall-functions), and two-layer zonal methods (adopting low Reynolds number amendments[15] to accurately resolve the near-wall region) will be considered. The computational results will be compared with the measurements of the unsteady turbulent pipe flow[8], for assessing the performance of these modelling approaches in predicting the transient convective heat transfer.

An assessment of the computational models for the transient case makes more sense, if the performance can be compared to that obtained for the stationary case. Therefore, as a starting point to the intended work, the statistically steady state heat transfer turbulent pipe flow is being considered, within a preliminary study. This phase also offers convenient means of improving some aspects of the numerical analysis, such as performing grid independencey studies etc., before starting with the transient analysis.

For statistically steady, turbulent pipe flow under fully developed conditions, there are several correlations in the literature, such as[16]

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \tag{1}$$

As a part of the abovementioned preliminary study, the predicted Nusselt numbers for the statistically steady turbulent pipe flow under fully developed conditions are compared with the values given by empirical relations. Such a comparison between the predictions and Eq. (1) is shown in Table 1, for Re=8000 and Re=30000. In these predictions (Table 1) a high Re k-ε turbulence model with equilibrium wall functions, and the Quick discretization scheme[9] were used and grid independent results were obtained. Special care was paid for the grid structure near the wall, for ensuring that the non-dimensional wall-distance y^+ for the first cell next to the wall, lies within the range of 30 – 60, as this is required for maximum accuracy by the employed method of wall functions.

Table 1. Comparison of predicted and empirical Nusselt numbers for statistically steady turbulent pipe flow under fully developed conditions, for Re=8000 and Re=30000.

	Nu, *predicted*	Nu, *empirical*	$\%\varepsilon$
Re = 8 000	28.5	26.6	7.1
Re = 30 000	75.0	76.4	1.8

The predictions agree rather well with the empirical correlation. For Re=8000, the deviation between the prediction and the correlation is substantially greater compared to the case with Re=30000. An explanation for this can be that the range of validity is given to be Re>10 000 for Eq. (1), whereas Re=8000 remains below that..

The steady state analysis as, a preliminary step, helps to form a basis for the following transient investigation, where the results obtained so far imply the convenience of the applied numerical strategies within this framework. The main objective of the present work, i.e. the transient analysis of the unsteady problem and a validation of models by comparisons with the transient measurements will be documented in the full paper to be presented at the conference.

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