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Study of the effect of entrance length on heat transfer to fibre suspensions in annular flow heat exchangers

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A B S T R A C T

In internal flow the boundary layer is unable to develop without eventually being constrained. There is no satisfactory general expression for the entry length in turbulent flow and it is approximately independent of Reynolds number and remains within 10–60D_h. Present experimental investigation has highlighted the effect of entry length (23 and 38D_h) on heat transfer to fibre suspensions in annular passage. It is observed that there is no significant variation of heat transfer coefficients with change in entrance length for water flow. Fibre suspensions flow at low consistency provides data with little variation whereas at higher consistency heat transfer coefficients data provides some variations but the trend remains similar for both short and long entrance lengths in the test section. Effects of fibre concentrations and flexibility in suspensions are providing similar trends in heat transfer irrespective of entrance length in annular flow, pipe flow and a larger annular gap.

1. Introduction

There has been a steady but consistent increase in demand for coaxial-pipe heat exchangers in the process industries and a renewed interest has been given to annular flow [1]. However in internal laminar or turbulent flow configuration the fully developed velocity profiles are parabolic for laminar and flatter for turbulent flows due to turbulent mixing in the radial direction. In fully developed flow the velocity profile does not vary in the flow direction. In fact in this region the pressure gradient and the shear stress in the flow are in balance. The length of the pipe between the start and the point where the fully developed flow begins is called the entrance length or calming length. The entrance length is a function of the Reynolds number of the flow.

The hydrodynamic entry length for laminar and turbulent pipe flow may be expressed by the Eqs. (1) and (2) respectively [2,3].

$$\left(\frac{x_{f,d,h}}{d}\right)_{lam} \approx 0.05Re \quad (1)$$

$$10 \leqslant \left(\frac{x_{fd,h}}{d}\right)_{turb} \leqslant 60 \quad (2)$$

In paper manufacturing process fibres are used in the suspension form at low consistency flowing to the head box of the paper machine from where it is discharged on the moving mesh under vacuum to produce paper as the final product. Thus behaviour of fibre in suspension form is playing a vital role in paper manufacturing process. It was reported earlier by the present authors about correlation of fibre and paper properties with heat transfer and friction loss characteristics of fibre suspensions [1,4] and that information could characterise fibres and aid the paper quality improvement. In the present study effect of entrance length on heat transfer and friction loss properties of suspensions in annular flow are taken into consideration. Performances of the industrial heat exchangers are evaluated in a regular basis by using standard equations. However the knowledge of entrance effect on suspensions could support the evaluation process.

Heat transfer and frictional loss of fibre suspensions in pipe flow, annular flow of different dimensions were studied by Kazi et al. [1] and Kazi [5]. From the studies of fibre suspensions in pipe flow, it is observed that numerous investigators selected different calming lengths for study of fibre suspension flow. There is no specified or accepted specification for the selection of entrance length for fibre suspension in annular flow.

In the study of heat transfer in annular flow, different investigators have chosen various entrance lengths depending on the hydraulic diameter of the test section. Middis [6] selected $20 \times D_h$ for study of heat transfer to fibre suspensions in annular

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Nomenclature

AR	without extension rod	T_S	wall temperature °C
BR	with extension rod	T_{TC}	temperature at thermocouple location °C
D_h	hydraulic diameter m	u	Fluid velocity m/s
d	pipe diameter m	ULo	*Pinus radiata* ultra low coarseness
d_m	point of maximum velocity on the velocity profile m	x	distance along x axis m
d_1	outside diameter of the inner tube of the annulus m	$x_{fd,h}$	hydrodynamic entry length m
d_2	inside diameter of the outer tube of the annulus m	ρ	density kg/m^3
Hi	*Pinus radiata* high coarseness	μ	dynamic viscosity kg/ms
q	heat flux W/m^2	λ	thermal conductivity W/m K
Re	Reynolds number		
r_h	hydraulic radius m		

flow. Study of heat transfer and subsequent fouling in evaporators with Kraft pulp black liquor was conducted by Branch [7] and Bremford [8] studied multiple effect evaporators for Kraft black liquor. Previous researchers have [7,8] used entrance lengths of 20 × D_h, whereas Hasson et al. [9] selected an entrance length of 38 × D_h for fouling in annular flow. An aim of this study is to investigate the effect of entrance length on heat transfer to fibre suspensions by changing the extension length of upstream at the test section.

2. Literature review

The study of heat transfer and frictional pressure loss in tubes and annular spaces has been conducted to provide a basis for designing heat exchangers and cooling systems in industries. Design data are available mainly for common fluids but there are no significant published data available for fibre suspensions.

Duffy et al. [10] studied heat transfer to fibre suspensions in annular flow. Water suspensions of Kraft softwood and hardwood pulps of various qualities were investigated in a simple coaxial pipe heat exchanger and heat transfer coefficient h_c values were calculated. They observed systematic differences in h_c values in the bulk velocity range of 0.4–2.4 m/s for different pulp suspensions at 0.4% concentration. They showed that h_c values at a specified flow velocity (1.5 m/s) and fibre concentration (0.4%) correlated well with specific fibre and paper properties. These results are similar to the data obtained by same authors in pipeline flow [11]. They have proposed that h_c could be used to monitor and therefore control pulp quality variations.

Robertson and Mason [12] suggested that a calming length for fibre suspension flows should be about 160 pipe diameters for the flow to become established and the fibre structured suspension stabilised. Hemstrom et al. [13] stated that the pressure gradient did not reach a steady value until about 80 pipe diameters downstream and was greater than the steady-state value before this point. Their results also showed that at 20D downstream the effect of a disturbance is only slight and decreases as concentration increases. Lee and Duffy [14] used the calming lengths upstream and downstream as 110 and 10 pipe diameters respectively, while investigating flowing Kraft pine fibres with concentrations ranging from 0.21% to 1.17% for turbulent flow at bulk velocities up to 9.17 m/s. Middis [6] selected 20 hydraulic diameters D_h in his studies of heat transfer to Bleached Kraft pine fibre suspensions of concentrations 0.08% to 1.03% in annular flow. Middis [6], Branch [7] and Bremford [8] used a calming length of 20D_h but Hasson et al. [9] selected a value of 38D_h in their heat transfer fouling study in annular flow.

More recent research has been focused on numerical simulation, spatial and orientation distributions of fibres in various flow fields, with some experimental validation. Lin et al. [15] studied numerically the motion of fibres in an evolving mixing layer and found that Stokes number is the key parameter to determine the spatial distribution of fibres. At a small Stokes number the fibres are homogeneously distributed in the flow. They found that the effects of both the density ratio and the fibre aspect ratio on the spatial and orientation distributions are small. Lin et al. [16] simulated numerically the orientation distribution of fibres in laminar and turbulent pipe flows. The simulated results are consisted with the experimental data available in the literature. They found more fibres are aligned with the flow direction with increasing Reynolds number in laminar flow but in turbulent flow the orientation distributions become more homogeneous and the fluctuation intensity of fibre velocity in the stream wise direction is larger than those in the other two directions. Olson et al. [17] derived equations of mean and fluctuating velocities in rotation and translation motion for rigid thin inertia less fibres moving in a turbulent fluid. They have derived rotational translational dispersion coefficients from the equations of fluctuating fibre velocity and the dispersion coefficients were shown to decrease with the increase of the ratio of fibre length to Lagrangian integral length scale.

Lin et al. [18] investigated theoretically and numerically the Rheological behaviour of fibre suspensions in a turbulent channel flow. The fluctuating equation for the orientation distribution function (ODF) of fibres was theoretically solved using the method of characteristics. They obtained relevant agreement with the experimental data. The shear stress of fibre suspensions increases with the decrease of first normal stress differences from the wall to the centre of the flow for varying Reynolds number. They obtained the orientation distribution of fibres in turbulent regime is much different from that in laminar regime. The randomising effect of the turbulent fluids leads to a broad orientation distribution, especially in the region near the centreline of the flow. Later Lin et al. [19] developed a new successive iteration method to calculate the mean orientation distribution of fibres and the mean and fluctuation correlated quantities of suspension in a turbulent channel flow and noticed drag reduction where Reynolds stress in the fibre suspensions were smaller than those in the Newtonian flow. They found that the amount of drag reduction augmented with the increase of the fibre mass concentration. Similar results were obtained experimentally by Kazi et al. [20]. Zhumin et al. [21] used combination of Finite element method and Brownian configuration field (BFC) method to simulate the fibre suspension flow in axisymmetric contraction and expansion passages. The results obtained for different geometry ratios are compared with the available constitutive models and experimental results. The predicted vortex length for dilute suspensions agrees well with experimental data in the literature and show the effect on vortex enhancement with the increase of the fibre volume fractions and the aspect ratios.