Validation of heat transfer data for fibre suspensions in coaxial pipe heat exchangers

S.N. Kazi, G.G. Duffy, X.D. Chen

Abstract

Heat transfer data obtained previously in a small coaxial pipe heat exchanger were validated using a new, larger annular-area test unit with longer calming section and axial entry flow. Water and two suspensions of long-fibre softwood Kraft pulps with fibres having different coarseness (mass/unit fibre length) values were used. Data in both systems were obtained over a range of flow rates with the fibre concentration at 0.4% and compared. Heat transfer coefficient $h_c$ was found to decrease with increasing annular gap size for both water and fibre suspension flow at equal velocities. Various fibre dimensions and fibre characteristics are also shown to vary systematically with $h_c$ at the same experimental conditions. The effect of hydrodynamic annular entry length on heat transfer and pressure loss using water and fibre suspensions (concentrations 0.2% and 0.4%) are also described. It was found that that extending the central calming extension rod made no significant difference to $h_c$ values at the low fibre concentration of 0.2%, and only small differences at the higher concentration of 0.4%. The successful validation of data from the smaller-annulus coaxial pipe heat exchanger show that the relationships among heat and momentum transfer and fibre characteristics and specific properties of paper are also valid for both heat exchangers.

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. An investigation of heat transfer and pressure drop in annular flow with internal coaxial heater was reported previously by the present authors but there was some concern with the results as spiralling flow was observed in some instances caused by the inlet flow being perpendicular to the tube axis. The calming length was regarded as insufficient to settle the flow in the test section and the flow pattern changed with velocity. The problem was exacerbated with fibre suspensions as the small annular gap meant that there was a stronger possibility for fibre–fibre bundling at the lower flow rates. Hence it was decided to rebuild the apparatus with axial flow entry, a longer calming length, and a larger annular gap.

The modified test section offered an opportunity to investigate the effects of calming length and hydraulic diameter on drag reduction and heat transfer in annular flow, that have not been reported in the literature previously. This and the validation of previous research into the flow of fibre suspensions in annular flow is the subject of this present work.

2. Literature review

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

Duffy et al. [1] studied heat transfer to fibre suspensions in annular flow. Various Kraft softwood and hardwood pulp water suspensions were investigated using 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 [2]. They have proposed that $h_c$ could be used to monitor and therefore control pulp quality variations.

It has long been known that pipe friction loss for fibre suspensions is diameter dependent [3] and decreases with increasing diameter. This is caused by the plug-like character at low flow rates [4]. The diameter effect is weaker in turbulent flow which is the
drag reducing regime for fibre suspensions [5,6]. Sharma [7] also found lower drag reduction in bigger diameter pipes. Patterson et al. [8] also showed that the diameter effect on drag reduction is extremely weak when comparisons are made at constant velocity instead of constant Reynolds number. Hence a study of the variation in annular gap is significant as nothing has been reported in the literature.

Robertson and Mason [3] 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. [9] 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 [10] 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 [11] selected 20 hydraulic diameters in his studies of heat transfer to fibre suspensions in annular flow. Previous researchers Middis [11], Branch [12], and Bremford [13] used a calming length of 20 Dh whereas Hasson et al. [14] selected a value of 38 Dh in their heat transfer fouling study in annular flow.

More recent research [15–17,18–22], has been focussed on numerical simulation, spatial and orientation distributions of fibres in various flow fields, with some experimental validation. Some investigations have extended knowledge in the shear flow behaviour of fibre suspensions [23–25]. The aim of present work, therefore, is to generate more experimental data for future development of a model for turbulent fibre suspensions flow.

3. Experimental

3.1. Experimental set-up

The measurement of heat transfer and pressure loss were performed in a new annular test section with dimensional details shown schematically in Fig. 1b, and the common flow loop in Fig. 1a. Details of the previously used test section are presented in Fig. 2. The magnitudes of the dimensional differences are stated in Table 1.

The pressure drop across the test section was measured with a differential pressure transducer at the tapping points designated in Fig. 1b. The Perspex test section has a stainless steel heating rod with a calming extension rod mounted concentrically. The heater rod has four embedded E-type thermocouples, with three located close to the internal heater just below the rod surface for surface temperature measurement. The fourth thermocouple is used to activate a safety trip in the event of high surface temperatures. The power supply to the heated section is controlled by the 10 amp-rated Variac. Current and voltage are measured and the signals are transmitted to the computer data logger through a Hewlett Packard data acquisition equipment. Further details are presented elsewhere [1,26].

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Dh</td>
<td>hydraulic diameter (m)</td>
</tr>
<tr>
<td>d</td>
<td>pipe diameter (m)</td>
</tr>
<tr>
<td>f</td>
<td>fanning friction factor</td>
</tr>
<tr>
<td>q</td>
<td>heat flux (W/m²)</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>rh</td>
<td>hydraulic radius (m)</td>
</tr>
<tr>
<td>TS</td>
<td>wall temperature (°C)</td>
</tr>
<tr>
<td>Ttc</td>
<td>temperature at thermocouple location (°C)</td>
</tr>
<tr>
<td>u</td>
<td>fluid velocity (m/s)</td>
</tr>
<tr>
<td>x</td>
<td>distance along x axis (m)</td>
</tr>
<tr>
<td>ρ</td>
<td>density (kg/m³)</td>
</tr>
<tr>
<td>τ</td>
<td>shear stress (N/m²)</td>
</tr>
<tr>
<td>μ</td>
<td>dynamic viscosity (kg/ms)</td>
</tr>
<tr>
<td>λ</td>
<td>thermal conductivity (W/mK)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equation</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>An annular cooler is shown with a heater and test section.</td>
<td></td>
</tr>
<tr>
<td>The flow meter is labeled as Flow meter.</td>
<td></td>
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<tr>
<td>The pressure tapping is labeled as Pressure tapping.</td>
<td></td>
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<tr>
<td>The extension rod is labeled as Extension rod.</td>
<td></td>
</tr>
<tr>
<td>The Perspex outer tube is labeled as Perspex outer tube.</td>
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</tr>
</tbody>
</table>

Fig. 1a. Schematic diagram of the experimental flow loop.

Fig. 1b. Schematic diagram of the coaxial-pipe, annular Test Section B with the larger hydraulic diameter and extended calming rod.
Different types of synthetic filaments were also investigated and details are given elsewhere [27].

Before each experiment, the pulp fibres obtained in sheets were soaked for approximately 24 h and then dispersed by the pump operating in recycle mode. Recycling was maintained for approximately 1 h to ensure optimum fibre dispersion and fibre wetting, and then for a further hour before any measurements were taken. A summary of experimental conditions is given in Table 1. Experimental corrections for the thermocouples \( \dot{j}/x \) values in both the cases before and after the annular test section modifications are presented in Table 2 according to the following equation:

\[
T_3 = T_{KC} - q/(\dot{j}/x)
\]  

(1)

Fibre concentration was measured at the beginning and end of each run and the measured values were always in agreement with differences less than 5%.

3.4. Data reduction

Reynolds number:

\[
Re = \frac{\rho ud}{\mu}
\]  

(2)

Hydraulic diameter:

\[
D_h = 4r_s = d_1 - d_2
\]  

(3)

\[
4r_h = \frac{d_2^2 - d_1^2}{d_2}
\]  

(4)

\[
d_m = \frac{d_2^2 - d_1^2}{\ln(d_2/d_1)}
\]  

(5)

The Reynolds number \( Re_2 \) of the outer portion of annular velocity profile is presented in the following equation:

\[
Re_2 = \frac{4r_s u \rho}{\mu}
\]  

(6)

The friction factor \( f_2 \) on the outer wall of the annulus bears the same relationship to the Reynolds Number, \( Re_2 \) as is given in Eq. (7) for circular tubes:

\[
f = 0.079Re^{-0.25} \quad (2.1 \times 10^4 < Re < 10^5)
\]  

(7)

The shear stress \( \tau_2 \) on the outer wall of the annulus is stated in the following equation:

\[
\tau_2 = f_2 \mu u^2/2
\]  

(8)

The shear stress \( \tau_1 \) on the inner wall is expressed by:

\[
\tau_1 = \tau_2 (d_2/d_1) \left( \frac{d_m^2 - d_1^2}{d_2^2 - d_m^2} \right)
\]  

(9)

4. Results and discussion

4.1. Data reproducibility

The rig with the new Test Section B (see Table 1) was calibrated using water. The procedural accuracy and reproducibility of data

Table 2

\( \dot{j}/x \) values before and after modifications.

<table>
<thead>
<tr>
<th>Location</th>
<th>( \dot{j}/x ) Values (before modification)</th>
<th>( \dot{j}/x ) Values (after modification)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25,000</td>
<td>20,000</td>
</tr>
<tr>
<td>2</td>
<td>12,500</td>
<td>14,286</td>
</tr>
<tr>
<td>3</td>
<td>14,286</td>
<td>20,000</td>
</tr>
</tbody>
</table>
were studied, and the data obtained compared with results with those from Test Section A used previously. The heat transfer results are presented in Fig. 3 with $h_c$ as a function of velocity, and the pressure drop data are presented in Fig. 4. Data reproducibility in both cases was very good with an rms error <3% within the confidence level of 95% for heat transfer, an average rms error <5% within the confidence level of 95% for the pressure drop data for the two water runs.

4.2. Fibre concentration effect

Bleached Kraft pine (BK) fibre of mean length 2.53 mm and coarseness 0.246 mg/m was used in the test runs to study the effect of fibres and fibre concentration on heat transfer. The data are present as $h_c$ versus flow velocity in Fig. 5 for four different fibre concentrations (0.1–0.4%) with water as the reference.

At velocities greater than about 0.5 m/s there is a spread of $h_c$ data below the water values similar to that obtained previously for pipe flow [27], as well as the data from the smaller Test Section A (see Fig. 6). At lower velocities (<0.5 m/s) there is a noticeable increase of $h_c$ above water values due to fibre–fibre interactions and some network fragment structures being formed. The thermal conductivity of fibre is less than that of water but fibres provide a solid path for heat conduction through the fibres themselves at low velocity which contributes to higher overall heat transfer coefficient values [11,27]. The data trends validate the results obtained from previous investigations.

4.3. Effect of fibre flexibility

Fig. 7 shows heat transfer coefficient $h_c$ as a function of velocity for different grades of pine, spruce and eucalyptus fibres at a concentration of 0.4%. For the pine fibre suspensions, $h_c$ decreases as both fibre length and fibre coarseness (mass/unit length) decrease, in agreement with data obtained in the smaller annular Test Section A (Fig. 8). The largest relative spacing for the data is at 1.5 m/s in both annular flow systems.

4.4. Hydraulic diameter/heat transfer to water and fibre suspensions

Data are presented in Fig. 9 for heat transfer coefficient as a function of flow velocity for water and two different pine fibre suspensions (Hi and ULo) in annular flow for the two different annular channel gaps or hydraulic diameters (0.0131 and 0.0333 m) [Annular Test Sections A and B]. Heat transfer coefficient values of the Hi and ULo pine fibre suspensions at 0.4% concentration are of the same relative order in both Test Sections A and B with respect to water.

Fig. 10 depicts $h_c$ as a function of Re (based on hydraulic diameter) for water and the Hi and ULo fibre suspensions at 0.4% fibre concentration. The Reynolds number corresponding to 1.5 m/s in the smaller annular Test Section A is 24,643 whereas
higher than all $h_c$ values in the larger annular Test Section B indicating that there are higher turbulence-augmented $h_c$ values in the smaller annular area test section.

For a more accurate comparison of $h_c$ values corresponding to each velocity [28], the shear stress at the wall of the inner heating rod has been calculated for both water and suspension flows. The $h_c$ values are presented as a function of shear stress in the two cases [smaller (S) and larger (L) hydraulic diameter] in Fig. 11. It is observed that $h_c$ increases with increasing wall shear stress in all cases.

As mentioned above, the $h_c$ values for water and fibre suspensions are always larger in the smaller annular Test Section A. Percentage differences are similar to the values of $h_c$ obtained as a function of velocity (Fig. 9). Thus either shear stress or velocity can be chosen as a variable parameter for comparison of $h_c$. From these investigations it is obvious that the $h_c$ increases with decreasing annular gap (hydraulic diameter of the annulus space) for water and fibre suspension flow but the trends are still systematic and of the same order of magnitude.

### 4.5. Effect of calming length on heat transfer

Fig. 12 shows heat transfer coefficient $h_c$ as a function of velocity for water and Kraft pine Hi and ULo coarseness at two concentrations 0.2% and 0.4% respectively for both annular test sections. The centrally located heating rod has a removable extension rod of the same diameter to aid in providing adequate calming. Data are presented in Fig. 12 without extension rod AR., and with extension rod BR. The typical increase in $h_c$ at low velocities is seen at both concentrations, with or without the calming extension rod. It can be observed that the data sets are in close agreement over the whole range of velocities for both fibre concentrations (about 13% lower than water values). This is significant as it shows that the upstream calming rod has little effect on the values obtained. A 65% increase in calming length in terms of hydraulic diameter (38 $D_h$ and 23 $D_h$) only produces a 5.8% maximum difference at higher velocities (>1 m/s).

### 4.6. Hydraulic diameter and pressure drop of water and fibre suspensions

Frictional pressure drop as a function of velocity for water and two different fibre suspensions (Hi and ULo) are presented in Fig. 13. The magnitude of pressure drop for water and ULo and
Frictional pressure drop is presented as a function of Re (based on hydraulic diameter $D_h$) in Fig. 14. The Reynolds number corresponding to 1.5 m/s in the smaller annular gap is 24,643, whereas in larger annulus, it is 82,934. It is observed that the order of magnitude of $\Delta P/L$ for water, ULo and Hi, is similar in both the cases of the smaller and larger annular gaps. At a particular Reynolds number (24,643 corresponding to 1.5 m/s in smaller annulus), the magnitude of $\Delta P/L$ for water, ULo, and Hi in smaller $D_h$ annular flow are respectively 99.7%, 99.2% and 98.8% higher than those of in the larger $D_h$.

Further analysis of unit frictional pressure drop $\Delta P/L$ in the annulus test section was extended by plotting the data as a function of wall shear stress on the outer surface of the inner rod. Fig. 15 represents frictional pressure drop as a function of shear stress in the smaller and larger annular gaps for water, Hi and ULo fibre suspensions at 0.4% concentration. $\Delta P/L$ clearly increases with the increase of shear stress in all the cases over the entire range of investigation.

It can be seen that when the shear stress level on the heater rod outer surface is equal in the two annular set-ups, $\Delta P/L$ levels in the smaller annular flow unit are higher than all those in the larger annular space unit (for water, ULo and Hi suspension). At a specified shear stress (9.6 N/m$^2$) corresponding to a velocity 1.5 m/s, $\Delta P/L$ values are 96.8%, 96.1% and 95.3% higher in the smaller annular unit than in the larger annulus (for water, ULo and Hi suspensions respectively). These values are similar to the values obtained in the case of $\Delta P/L$ versus velocity (Fig. 13). It can be concluded that in the heat transfer study the observed values of $h_c$ in the smaller annulus are almost same percentages higher than those of larger annulus, irrespective of whether $h_c$ is presented as a function of velocity or shear stress.

4.7. Study of pressure drop in the test section with long and short calming lengths

Fig. 16 depicts pressure drop as a function of velocity for water flow in the annular test section with both the extended BR and with virtually no calming lengths AR (after removal). The pressure drop was measured across the whole test section.

At a specific velocity of 1.5 m/s, the pressure drop is about 23.5% lower than with longer calming length. The difference increases with increasing velocity. Removing the extended inlet-calming length rod from central heater reduces the constriction and calming of the inlet flow, causing fluid impact on the leading face of the heater rod that affects the magnitude of the pressure loss.
was selected which was similar to values chosen for pipeline studies. The measuring techniques and procedures used with the smaller Test Section A had been of concern initially because of observed spiral entry flow, and the potential ongoing effect of the smaller-than-normal calming entry length. The research reported here with the improved set-up of coaxial pipe heat exchanger (Test Section B), resulted in a large amount of data that compared favourably with the previous experimental data obtained from the coaxial pipe heat exchanger of different dimensions. Clearly the concerns were allayed, and the results confirm that heat transfer coefficient and pressure drop measurements are promising ways of monitoring fibre variations and hence pulp quality.

Some of the extensive correlations relating both fibre characteristics and the properties of paper made from the same fibres, are presented in the Appendix A. The results of this study using a larger annular space (Test Section B) further support the validation of that the comparable data obtained with the original heat exchanger [1].

5. Conclusions

The results from this present study confirm that the data obtained in a smaller, annular-space coaxial heat exchanger are valid even though the results were not as accurate as those obtained in the larger annular test unit. Heat transfer to fibre suspensions is observed to increase with decreasing hydraulic diameter for water and fibre suspensions, either at equal velocities or equal shear stress levels. Hence, either shear stress or velocity can be used to compare $h_c$ values calculated from data obtained in an annular space because experimentally, the similar $\Delta h$ were obtained in two different annular test sections with different hydraulic diameters. Heat transfer to water or to fibre suspensions of low concentrations (0.2%) does not change significantly with change of calming length but at higher fibre concentration (0.4%) the difference is detectable but still very small.

Appendix A

Graphical comparison of fibre and paper properties as a function of $h_c$ and $\Delta P/L$ of fibre suspensions flowing through the smaller Annular Test Section A and Larger Annular Test Section B for direct comparison.

($L = \text{mean fibre length}$, $D = \text{mean fibre diameter}$, $P = \text{fibre perimeter}$, $t = \text{fibre thickness}$).

A.1. Smaller annular space

A.1.1. Test Section A

Fibre properties versus $h_c$ (see Figs. A1–A6).

Paper properties versus $h_c$ (see Figs. A7–A10).

Fibre properties versus $\Delta P/L$ (see Figs. A11–A16).

Paper properties versus $\Delta P/L$ (see Figs. A17–A20).

Appendix B

B.1. Larger annular space

B.1.1. Test Section B

Fibre properties versus $h_c$ (see Figs. B1–B6).

Paper properties versus $h_c$ (see Figs. B7–B10).

Fibre properties versus $\Delta P/L$ (see Figs. B11–B16).

Paper properties versus $\Delta P/L$ (see Figs. B17–B20).
Fig. A1. Length $l'$ versus $h_c$.

Fig. A2. $L'/P$ versus $h_c$.

Fig. A3. $P/t$ versus $h_c$.

Fig. A4. Coarseness versus $h_c$.

Fig. A5. Fibre area versus $h_c$.

Fig. A6. Relative fibre number versus $h_c$.

Fig. A7. Paper tensile and tear indices versus $h_c$.

Fig. A8. Burst index versus $h_c$. 
Fig. A9. Light scattering coefficient versus $h_c$.

Fig. A10. Formation index versus $h_c$.

Fig. A11. $L'$ versus $\Delta P/L$.

Fig. A12. $L'/P$ versus $\Delta P/L$.

Fig. A13. $P/t$ versus $\Delta P/L$.

Fig. A14. Coarseness versus $\Delta P/L$.

Fig. A15. Fibre wall area versus $\Delta P/L$.

Fig. A16. Relative fibre number versus $\Delta P/L$. 
Fig. A17. Tensile and tear indices versus $\Delta P/L$.

Fig. A18. Burst index versus $\Delta P/L$.

Fig. A19. Light scattering coefficient versus $\Delta P/L$.

Fig. A20. Formation index versus $\Delta P/L$.

Fig. B1. Length $L'$ versus $h_c$.

Fig. B2. $L'/P$ versus $h_c$.

Fig. B3. $P/t$ versus $h_c$.

Fig. B4. Coarseness versus $h_c$. 
Fig. B5. Fibre wall area versus $h_c$.

Fig. B6. Relative fibre number versus $h_c$.

Fig. B7. Paper tensile and tear indices versus $h_c$.

Fig. B8. Burst index versus $h_c$.

Fig. B9. Light scattering coefficient versus $h_c$.

Fig. B10. Formation index versus $h_c$.

Fig. B11. $L'$ versus $\Delta P/L$.

Fig. B12. $L'/P$ versus $\Delta P/L$. 


References


