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Development of a more robust correlation for predicting heat transfer performance in oscillatory baffled reactors

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ABSTRACT

The oscillatory baffled reactor has been well-characterised in most areas of flow reactor performance (mixing, mass transfer, multi-phase operation *etc.*), with the exception of heat transfer, where comparatively few data exist in the literature. Here, a robust investigation of heat transfer in the "standard", 26 mm diameter, oscillatory baffled reactor is presented which goes beyond the parametric limitations of previous studies.

5-fold Nusselt number increases over steady unbaffled flows are shown to be achievable. The maximum enhancement attributed to the oscillatory flow component alone compared to the steady-flow, baffled case is shown to be 1.7-fold. The degree of heat transfer enhancement is shown to plateau when the oscillatory flow Reynolds number exceeds 1300, indicating that a radial mixing limit has been reached.

A new correlation for predicting heat transfer coefficients in oscillatory baffled reactors has been developed. Based on the data generated here, it is accurate to ± 30% across the experimental range of the study. The correlation has been further validated using literature data, and shown to be the most robust correlation to date for predicting heat transfer performance in oscillatory baffled reactors.

1. Introduction

The oscillatory baffled reactor (OBR) is a continuous tubular flow reactor in which an oscillatory flow is imposed onto a relatively small net flow within a baffled tube. This results in the formation and dissipation of vortices either side of the baffles throughout each flow reversal cycle, effectively creating a series of well-mixed "tanks-in-series". This leads to plug flow behaviour even though net flow conditions are laminar. This allows the rate of mixing, heat and mass transfer to be decoupled from the net flow rate, which in turn largely decouples length – turbulence – velocity design.

Oscillatory baffled flows are characterised using four dimensionless groups:

- The net flow Reynolds number, Re_n, which defines the net flow condition.
- The oscillatory Reynolds number, Re_o, which gives a measure of the oscillatory flow intensity.
- The velocity ratio, Ψ. The ratio of the oscillatory flow to net flow intensity.
- The Strouhal number, Sr. A measure of eddy propagation in the pipe.

$$Re_n = \frac{\rho u D}{\mu} \tag{1}$$

$$Re_o = \frac{x_0 \omega \rho D}{\mu} \tag{2}$$

$$\Psi = \frac{Re_o}{Re_n} \tag{3}$$

$$Sr = \frac{D}{4\pi x_0} \tag{4}$$

Here ρ is the fluid density (kg/m^3), u the superficial net flow velocity (m/s), D the pipe diameter (m), μ the fluid viscosity (kg/ms), x_0 is the centre-to-peak amplitude of oscillation and ω the angular frequency of the oscillation cycle ($\omega = 2\pi f$, where f is the frequency of oscillation in Hz).

Mixing [1–4] and mass transfer [5,6] in OBRs have been well defined in previous studies, however there has been relatively little research into heat transfer. Most recently, Solano et al. [7] studied heat transfer enhancement in helically baffled meso-scale OBRs as part of a CFD study into the flow structures generated in this type of OBR. Their results showed a Nusselt number enhancement of up to 4-fold compared to steady, unbaffled flow, which was well explained by the velocity

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streamlines and vectors from the flow-pattern analysis section of the paper. However, no experimental validation was presented and no correlation was proposed for predicting OBR Nusselt numbers.

Mackley et al. [8] presented the results of a preliminary study on heat transfer in pulsatile and oscillatory baffled flows. The preliminary data obtained in this study showed that a Nusselt number enhancement of up to 6-fold could be achieved using oscillatory baffled flows compared to steady flow in smooth tubes. Mackley and Stonestreet [9] then expanded on the findings of the previous paper in a further experimental study over a wider range of oscillation frequencies and amplitudes. They showed that up to a tenfold increase in the Nusselt number is possible using oscillatory baffled flows compared to steady, unbaffled tubes. A Nusselt number correlation for oscillatory baffled flows was devised (Eq. (5)). While the authors acknowledged that this was a purely phenomenological model based only on their data set, they did also state that it shows the correct behaviour, thereby allowing it to be used over an extended range of Re_n and Re_o. The inclusion of the Prandtl number (Pr) suggests that the correlation should be valid for all liquids, although only one fluid was evaluated in the study, an engine oil of average Pr = 73. As a result, this correlation is accepted as the best estimate to predict heat transfer coefficients in OBRs [10].

$$Nu = 0.0035Re_n^{1.3}Pr^{\frac{1}{3}} + 0.3\left[\frac{Re_o^{2.2}}{(Re_n + 800)^{1.25}}\right] \quad (5)$$

In Eq. (5) the first term corresponds to the steady-flow contribution to heat transfer and is similar to the Dittus-Boelter correlation for heat transfer in turbulent flows. The second term accounts for the heat transfer enhancement observed due to the oscillatory flow component. The correlation suggests that the enhancement observed wanes as Re_n becomes larger than Re_o meaning that the Nusselt number tends towards that for steady-baffled flow at higher net flow rates. For constant net flow Reynolds number, the Nusselt number will increase according to an approximately squared relationship for increase in the oscillatory flow Reynolds number.

It appears that the correlation is not valid for liquids of relatively low Pr. For example, if the correlation is used to predict the Nusselt number of an OBR using water as the working fluid, the results displayed in Fig. 1 are obtained (mean fluid temperature of 40 °C, mean Pr of 4.43).

Fig. 1 shows that the correlation predicts that, for constant Re_o, minima exist as Re_n increases. This behaviour was not observed in the study by Mackley and Stonestreet [9] and there are no reports of it occurring. The explanation for this result lies in the form of the correlation equation and the relative size of the two terms. In Fig. 1, the second term in the correlation reduces in size as the net flow Reynolds number increases by an amount which cannot be sustained by the increase in the first term, thereby leading to a minimum in the function. This behaviour is masked at higher values of Pr (as in the original study, Pr = 73), as in all cases the value of the first term is significantly larger than the second term. This result suggests that the correlation may not be valid for lower Pr liquids and that further investigation is required, to find a more general expression.

It is also necessary to perform heat transfer experiments over a wider range of oscillatory flow intensities. In Mackley and Stonestreet [9] the highest oscillatory Reynolds number tested was 800. Hence, for $Re_n > 800$ (around 40% of the dataset) the velocity ratio was less than 1. Under these conditions, full flow reversal would not be achieved and is not representative of general OBR design (velocity ratios of greater than 2 are typically used to maintain the compact design of the OBR). It is therefore possible that the hypothesis that oscillatory flow has little effect on heat transfer at higher net flows and that the heat transfer coefficients tend towards those of steady baffled flows may only be due to the fact that the oscillation intensity investigated was too weak.

The aim of this paper is to increase understanding of heat transfer phenomena in OBRs and to generate a new, robust correlation for predicting the Nusselt number by exploring a greater parametric range than previously studied.

2. Experimental

2.1. Materials, apparatus and methods

A laboratory-scale countercurrent annular tube heat exchanger was used to conduct the experiments, as shown in Fig. 2 (schematic diagram) and Fig. 3 (photograph of rig). The inside tube (OBR-side) was a 26.2 mm i.d. copper tube with a wall thickness of 0.9 mm, while the outer-tube (shell-side) was a 39.6 mm i.d. copper tube. The active length of the heat exchanger was 500 mm. Orifice baffles were used on the OBR-side (13 mm orifice; 52 mm baffle spacing).

The cold fluid flowed on the shell-side of the heat exchanger and was provided by mains water at a constant 3 l/min flowrate. The cooling flow was at a temperature of 12–15 °C throughout the experimental programme meaning that variation in thermophysical properties were negligible.

Two OBR-side fluids were used: deionised (DI) water and 25 wt%

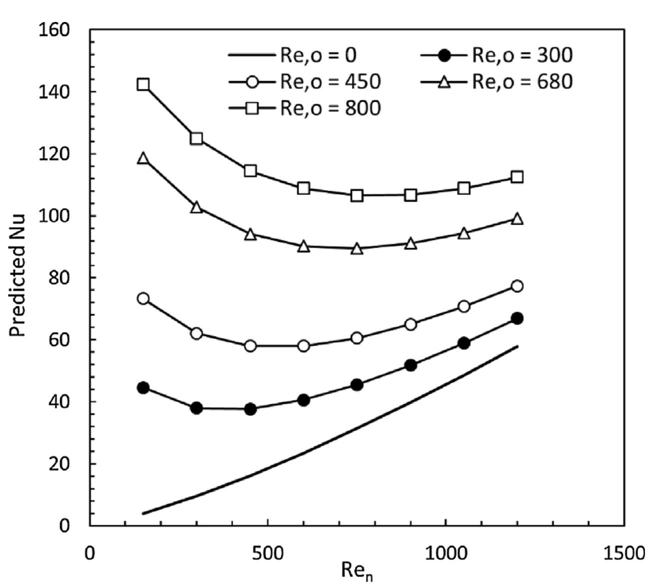

Fig. 1. Plot of predicted Nusselt number vs Re_n and Re_o for water.

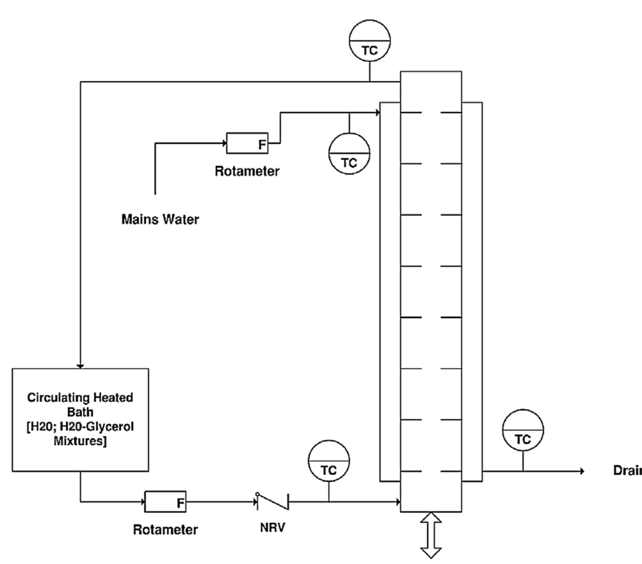

Fig. 2. Schematic of rig.