Proceedings of the 18th UK Heat Transfer Conference

9-11 September 2024, Birmingham

UKHTC2024-119

ENHANCEMENT FOR LAMINAR FLOW USING STATIC IN-TUBE DEVICES

Hamzah Sheikh[1], William Osley[1], Stephen Pitt[1], Oluwatobiloba Henry[2], Andrei-Leonard Niçusan[2],
Jonathan Seville[2], Adriano Sciacovelli[2], Peter Drögemüller[1*]

[1]Centre for Flow Processing (CALGAVIN Ltd.), Alcester, Warwickshire, B49 5ET, United Kingdom

[2]School of Chemical Engineering, University of Birmingham, Birmingham, B15 2TT, United Kingdom

1. ABSTRACT

The heat transfer benefits of static in-line enhancement devices for tubular heat exchangers in laminar flow have been investigated using experimental and theoretical approaches. A high viscosity heat transfer facility was used to characterise an existing wire matrix insert (hiTRAN) and a new plate type insert (hiVISC), with additional studies using CFD. Positron emission particle tracking (PEPT) was employed to visualise flow in an otherwise opaque system. hiTRAN and hiVISC® inserts displayed higher efficiency heat transfer in low Reynolds number laminar flows in comparison to commonly used alternative insert designs.

2. INTRODUCTION

Increasing efficiency of industrial plants is an ongoing endeavour, with efforts to reduce wastage, carbon emissions and production times. High viscosity flows in the chemicals, oils, polymer production, and food industries are subject to poor heat transfer coefficients in exchangers, restricting heat recovery and integration capabilities. These processes account for ~12% of the UK energy demand in the form of process heating and cooling. Of this heat, however, 20-50% of energy used in industry is wasted due to poor heat transfer [1].

These high viscosity fluids result in low Reynolds number laminar flow in heat exchangers, where increasing velocity has a small effect on the tube-side heat transfer coefficient. Furthermore, these processes can be affected by in-tube natural convection effects, where the surface available for heat transfer is reduced due to a temperature pinch. In the case of reactions in the flow, the deep laminar regime can cause difficulties due to high axial distribution of reactants, dissimilar to an ideal plug flow.

In-line static mixers and turbulators have been used to improve these issues, particularly where flow is viscous and prone to poor heat transfer and mixing. A range of devices are commercially available, predominantly static mixers, which enhance exchanger performance at the cost of pressure drop. These devices are often designed to cut the flow and incorporate sections of fluid into one another through forced channels or paths, and although these inserts can improve homogeneity of the fluid, a significant amount of energy is lost through friction and therefore requires more pumping power. Furthermore, improving mixedness does not necessarily result in more efficient heat transfer or improved residence time distributions.

The advantages of using two types of in-line turbulator in viscous applications, a wire matrix-based insert (hiTRAN), and a new plate type insert (hiVISC) were investigated. These devices are designed for enhancing performance in tubular reactors, specifically improving residence time distributions and tube-side heat transfer.

3. METHDOLOGY

3.1. Experimental

3.1.1. Heat transfer and pressure drop characterisation

Heat transfer enhancement and pressure drop penalty were measured using the high viscosity flow rig (HVFR), consisting of a heating test section and a cooling test section which were operated simultaneously. Each test section consisted of a tube-in-tube configuration, with water acting as the service fluid on the shell side flowing counter-currently. Glycerol was used as the process fluid due to its Newtonian behaviour and range of viscosities at the operational temperatures between 10 – 60 °C. Tube side and shell side temperatures were taken on both inlets and outlets using a bespoke probe design for the accurate measurement of bulk temperature. Each test section was also fitted with

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*Corresponding Author: peter.droegemueller@calgavin.com

a differential pressure sensor, which measured the in-tube pressure drop. The HVFR was also fitted with a Coriolis flowmeter and a bypass section to measure glycerol viscosity prior to each test run.

Experiments were conducted by inserting a tubular enhancement device into each test section and measuring the heat transfer over a range of flowrates and temperatures by adjusting the gear pump frequency using a frequency inverter. Temperatures were controlled using two separate flow loops, one for cooling coupled with a chiller unit and one for heating which used a controlled tank with an immersion heater.

3.1.2. Positron emission particle tracking

Measurements of Lagrangian flow paths were conducted by the positron emission particle tracking (PEPT) technique, enabling a visualisation of in-tube fluid movement with the influence of inserts. The method utilised a simple test facility, which incorporated a test section where fluid was maintained isothermally. Flow of glycerol was induced by a variable speed pump, and a single positron-emitting tracer particle was injected into the tube. The tracer continually emitted positrons, which annihilate with local electrons, each annihilation resulting in two back-to-back 511 keV gamma rays. These pairs of gamma rays were detected by two cameras, for which the resulting data were algorithmically constructed into space-time tracer positions [2]. These particle trajectories showed the influence of the tested inserts on flow paths in laminar flow.

Fig. 1 hiVISC particle tracking results using PEPT. Particle positions are shown as an axial projection, coloured by velocity where high velocity is depicted darker than low velocity.

3.2. Computational fluid dynamics

Verified computational fluid dynamics (CFD) models were used to extend the scope of study for each of the devices. A computational model of the HVFR test sections was constructed in Ansys Fluent, and extensively calculated to minimise errors. The computational setup mimicked the conditions of HVFR tests, where heat transfer and pressure drop results accurately matched those observed in experiments. These results were then extended into deep laminar flow, by computationally increasing the fluid viscosity and thereby reducing the Reynolds number by an order of magnitude. Furthermore, particle tracking experiments were also recreated with good agreement.

4. RESULTS

4.1. Pressure drop

Baseline experiments were conducted using the HVFR with no tube internals, where isothermal results in pressure drop matched theoretical expectations. Experiments were conducted for Re = 0.1 - 100, by adjusting the pump frequency and changing the temperature of glycerol. Inserts increased the pressure drop observed in the test sections. For hiTRAN, increasing the packing density resulting in an increase in pressure drop, and the same trend was observed when reducing the pitch for hiVISC.

4.2. Heat transfer

As with pressure drop tests, initial baseline experiments for tube side heat transfer were conducted for the test sections without internals using the HVFR. The same tests were then conducted for each of the inserts. All inserts increased the heat transfer coefficient in comparison to the empty tube. Low density hiTRAN had the lowest heat transfer enhancement, which increased with packing density. Similarly, heat transfer coefficient increased with a reduction in pitch for hiVISC.

An efficiency for each insert was calculated by computing a ratio between heat transfer enhancement over pressure loss in comparison to the empty tube results. Heat transfer coefficient was non-dimensionalised by calculating j-factor:

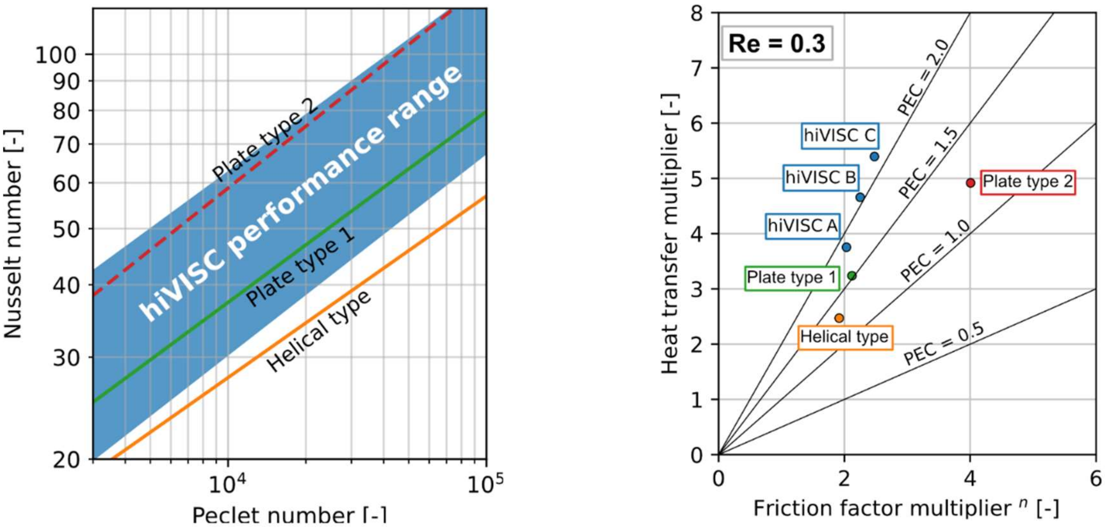
$$j = \frac{Nu}{Pr^n} \tag{1}$$

Pressure drop was non-dimensionalised by calculating Darcy friction factor, f, then, insert efficiency, η, was calculated as follows:

$$\eta = \frac{j_{insert}/j_{empty}}{\left(f_{insert}/f_{empty}\right)^m} \qquad (2)$$

Using this definition, insert performance could be evaluated against the empty tube. η = 1 represented empty tube performance, whereas an increased value indicated increased heat transfer with less pressure penalty than an equivalent length of empty tube required for the same heat transfer.

hiTRAN inserts show an increasing η with increasing *Re*, indicating best performance where $Re > 50$, particularly for high packing density. hiVISC shows up to $\eta = 2.3$ at very low *Re* (< 1), which increases as *Re* increases. Trends show η may reduce as $Re > 100$. Both sets of inserts show advantages over commonly used helical type inserts often used for viscous heat transfer enhancement.



(a) **(b)**

Fig. 2 hiVISC experimental performance results compared to commercially available static mixer inserts, **(a)** shows the hiVISC heat transfer (Nu) against Peclet (Pe) number, and **(b)** shows the heat transfer and friction factor multiplier results with η (PEC) values shown in black lines.

5. CONCLUSION

Using a variety of experimental methods, we characterised two types of tubular enhancement device (hiTRAN and hiVISC) in terms of pressure drop and heat transfer enhancement in high viscosity applications. Results showed both sets of inserts deliver efficient enhancement, where pressure drop penalty was a fraction of the heat transfer enhancement. The novel PEPT technique accurately demonstrated effects on flow in an otherwise opaque system, showing the mechanisms for efficient heat transfer. Applying these devices in flow reactors, viscous heat exchangers and other units can provide significant benefits in reducing costs, footprint, energy usage and carbon emissions.

ACKNOWLEDGMENT

We thank Yui Ming Kan for PEPT tracer production and Prof. Tzany Kokalova Wheldon, Director of the Birmingham Positron Imaging Centre. This project was supported by UKRI Innovate UK Smart Project no. 57083.

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