HIGH-EFFECTIVENESS MICRO-EXCHANGER PERFORMANCE

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INTRODUCTION

Heatric has been involved in the commercial design and manufacture of "micro/milli" scale heat exchange core matrices called Printed Circuit Heat Exchangers (PCHEs) since 1985, following several years of developmental work at the University of Sydney. PCHEs are single-material (usually metal) matrices formed by diffusion bonding together plates into which fluid flow passages have (usually) been formed by photo-chemical machining.

PCHEs are "compact" relative to conventional heat exchangers, but they are not necessarily "small". Single units of up to 100 tonnes have been manufactured, and clearly these are only "compact" in comparison to the 500 tonne alternatives. Currently there are thousands of tons of such cores in hundreds of services - many of them arduous duties on offshore oil and gas platforms where the size and weight advantages of compact structures are of obvious major benefit. Whilst these cores are predominantly involved in two-fluid heat exchange, at pressures up to 500 bar, there is also a long history of their application to more complex integrated fluid processing applications. Indeed even in the development stage of PCHE technology at the University of Sydney operations such as multi-stream counterflow heat exchange, rectification, stripping, mixing, absorption, boiling, condensation and separation were incorporated into compact integrated process modules. The potential for application of PCHEs to temperature control in chemical reaction has also been long recognised, with potential benefits anticipated in areas such as compactness, operability, efficiency, safety and cost.

In this paper we consider single-phase heat transfer and heat exchanger effectiveness in PCHEs at Reynolds Numbers below 1500 - the "laminar" regime - which is commonly encountered in counterflow heat exchangers.

HEAT EXCHANGER DESIGN CONSIDERATIONS

The design of a heat exchanger requires the reconciliation of a large number of considerations, including:

- Achieving the required thermal effectiveness (boundary temperatures) within the allowable pressure drops
- Minimising the size and/or mass of the exchanger (particularly in micro-devices)
- Minimising the cost of the exchanger
- Ensuring valid mechanical design for pressure containment at the design temperature
- Configuring a suitable shape for the exchanger to fit within a nominated envelope
- Choosing suitable materials of construction
- Making suitable provision for connecting the fluids, without inducing undue fluid maldistribution

PCHE manufacturing and design techniques provide a remarkably powerful means of optimising heat exchanger designs which meet the various mandatory requirements. The facility for containment of very high pressure and support for high degrees of process intensification using corrosion resistant materials are of particular note relative to other "plate" heat exchange technologies.

Passage dimensions

Minimum passage size clearly bears directly on the compactness of the cores. The most important consideration in selecting the minimum passage dimension is the cleanliness of the fluids, as smaller passages require greater stringency in the preceding clean-up of the fluids. Even with perfectly clean fluids, though, other factors come into play in determining optimum passage size, including the combination of allowable pressure drop, the required contact effectiveness and the sheer size of the duty. It is one thing to configure a cross-flow micro-exchanger for a duty of 100 W, but yet another to develop a cost effective counterflow design to handle 10 MW.

Generally such considerations result in minimum passage dimensions in PCHEs falling below 2 mm, but not often below 0.2 mm. In this range of dimensions it is inevitable that Reynolds Numbers are considerably lower than in conventional heat exchangers, where clearances are an order of magnitude larger. As a result, PCHEs often operate at and below the transition Reynolds Numbers (2000 to 4000), where frictional and heat transfer behaviour is uncertain in straight tubes.

Surface characteristics

The fundamental objective for a heat exchanger is to achieve a specified thermal effectiveness within the specified pressure drop constraints. Micro-devices need be no less flexible in meeting pressure drop constraints than conventional devices, despite the smaller passage dimensions. In order to achieve this objective, a knowledge of the frictional and heat transfer characteristics of the heat exchange surfaces is required. Relevant information can be presented in the form of heat transfer j factor and Fanning friction factor (f) charts.

Figure 1 shows j and f for a series of PCHE surfaces of increasing flow tortuosity (increasing from 1 to 6), the increasing tortuosity being evidenced by increasing j and f at a given Re. (There are of course many means of inducing increases in j and f in micro-devices through flow disruption, and Figure 1 characterizes only one method.) Some transition uncertainty is evident in the heat transfer behaviour of Surface 1 above Re of 2000.

Another view of the heat transfer behaviour of the surfaces is given in Figure 2, which charts the Nusselt Number increment over fully-developed laminar levels, $(Nu - 3.5)/Pr^{1/3}$, versus Re. The curves for all levels of tortuosity tend to asymptote to zero below Re of 100, indicating that this method of heat transfer enhancement is becoming far less effective at low Reynolds Numbers. Low-tortuosity Surface 1 maintains laminar-like behaviour to Re of over 1000, where the Nu of maximum-tortuosity Surface 6 is may be five times higher.

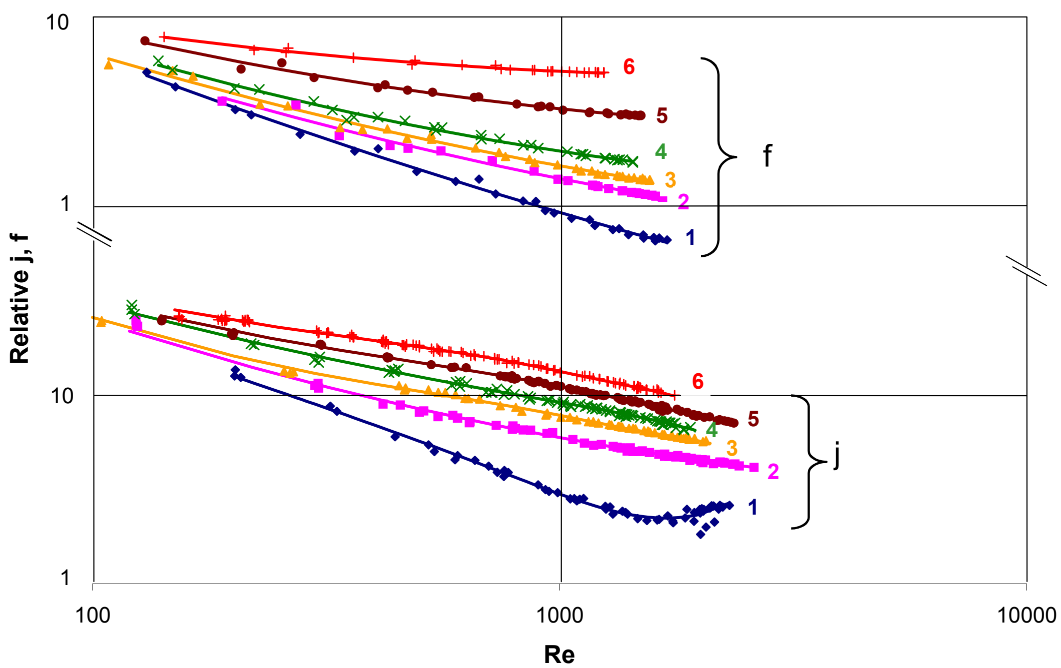

Figure 1: Relative heat transfer j factors and Fanning friction factors f versus Reynolds No. and flow tortuosity

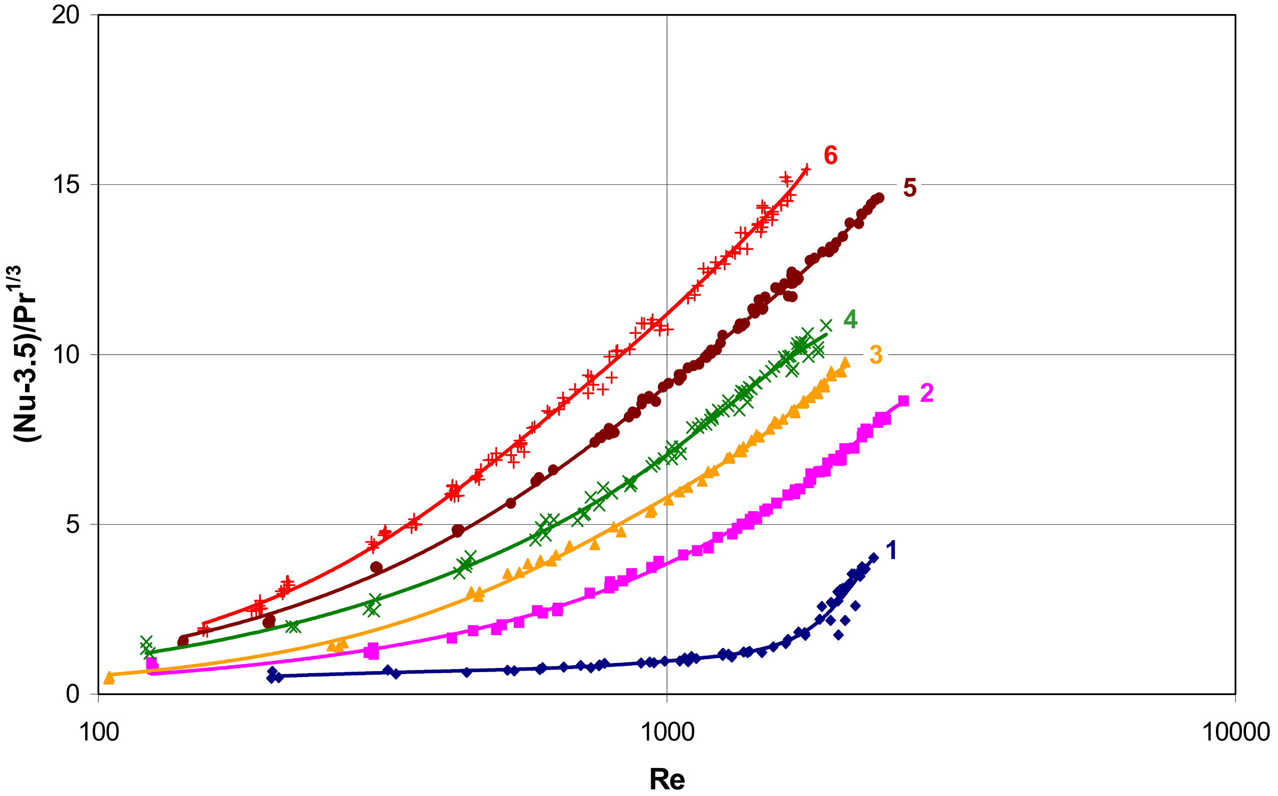

Figure 2: Nusselt No. increment over fully-developed laminar flow level versus Reynolds No. and flow tortuosity

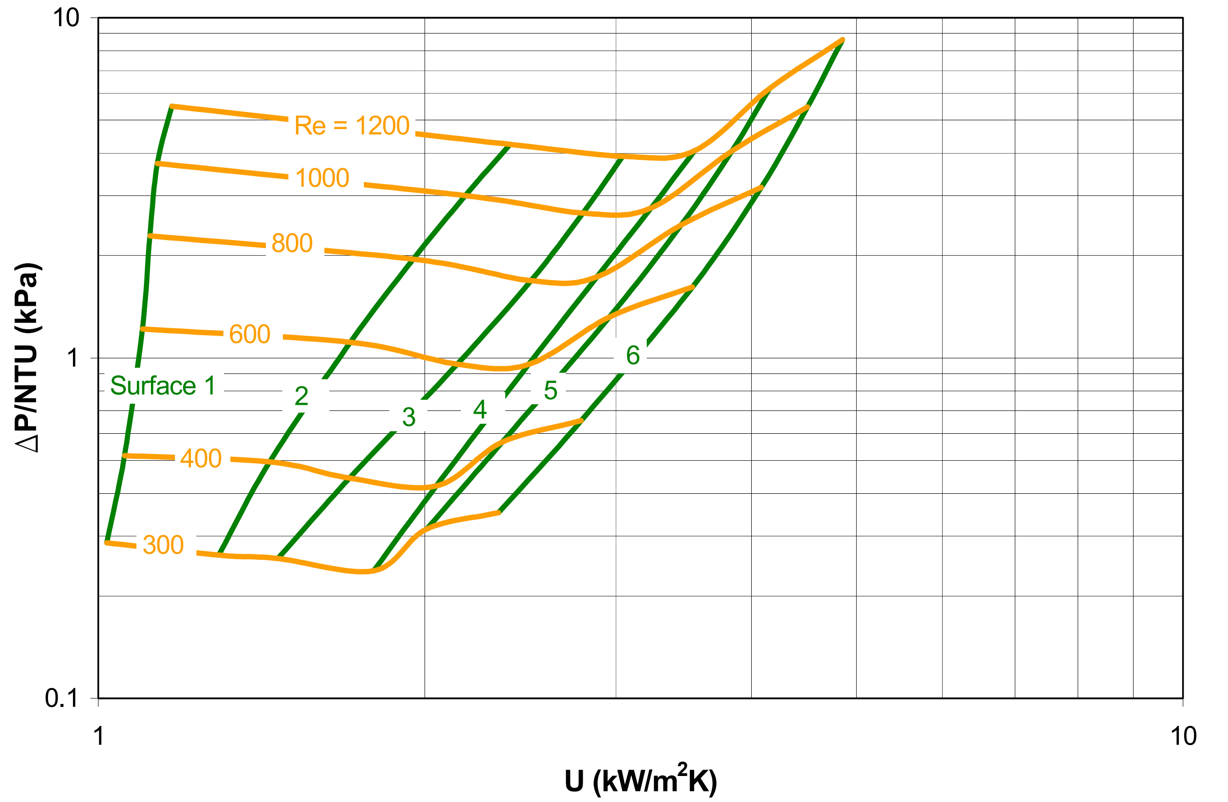

Figure 3: Pressure drop per NTU versus overall heat transfer coefficient for water/water counterflow heat transfer, heat capacity ratio of 1, mean temperature 45°C

Inspection of Figure 1 suggests that f increases more quickly than j at higher Re, raising the obvious question: is there any net benefit to heat exchanger sizing in using the higher tortuosity surfaces? This question can be answered with the assistance of Figure 3, which charts the ratio of the allowable pressure drop per heat transfer unit (△P/NTU) versus the overall heat transfer coefficient (U) in water/water counterflow exchangers employing surfaces 1 to 6. Note that the ratio △P/NTU incorporates the key thermal performance specifications of pressure drop and effectiveness, whilst U determines the size of the exchanger. For a given (specified) △P/NTU, the exchanger with the highest U will be the smallest. Taking the case of △P/NTU = 5 kPa as an example, Surface 1 would operate with U of 1.5 kW/m^2K, whereas Surface 6 would operate with U of 4.5 W/m^2K. (Both would operate with a Reynolds Number of about 1200.)

Therefore an exchanger employing Surface 6 would be only one-third the size of the exchanger employing Surface 1, confirming that very substantial sizing enhancement is achievable with tortuous flow surfaces.

Exchanger shape

Whilst Figure 3 provides a valid indication of the achievable heat transfer coefficients in water/water counterflow exchangers using various PCHE surfaces, there may be further considerations which become relevant under some circumstances. If, for example, very high effectiveness (>97%) were specified, an exchanger with over 30 NTUs would be required for a heat capacity ratio of 1. Such an exchanger would require passages with a very high length-to-diameter ratio, and a small cross-flow region near the inlets/outlets: the obvious risk is that the exchanger would be inconveniently long and thin, even though remaining "compact" in the sense that it retained relatively low volume and mass.

In order to obtain an exchanger with a more convenient shape, it may be helpful to "fold" the passages, even though this creates the possibility of detrimental short-circuit heat transfer between the successive passage folds. The results of such an approach are shown in Figure 4, where the performance of the long, thin counterflow exchanger is compared with that of squatter units of the same heat exchange area which may be more conveniently shaped for installation. Clearly there is a price to pay in terms of loss of performance for the short-circuit heat transfer at high effectiveness, but this can be quantified and may be justified under some circumstances.

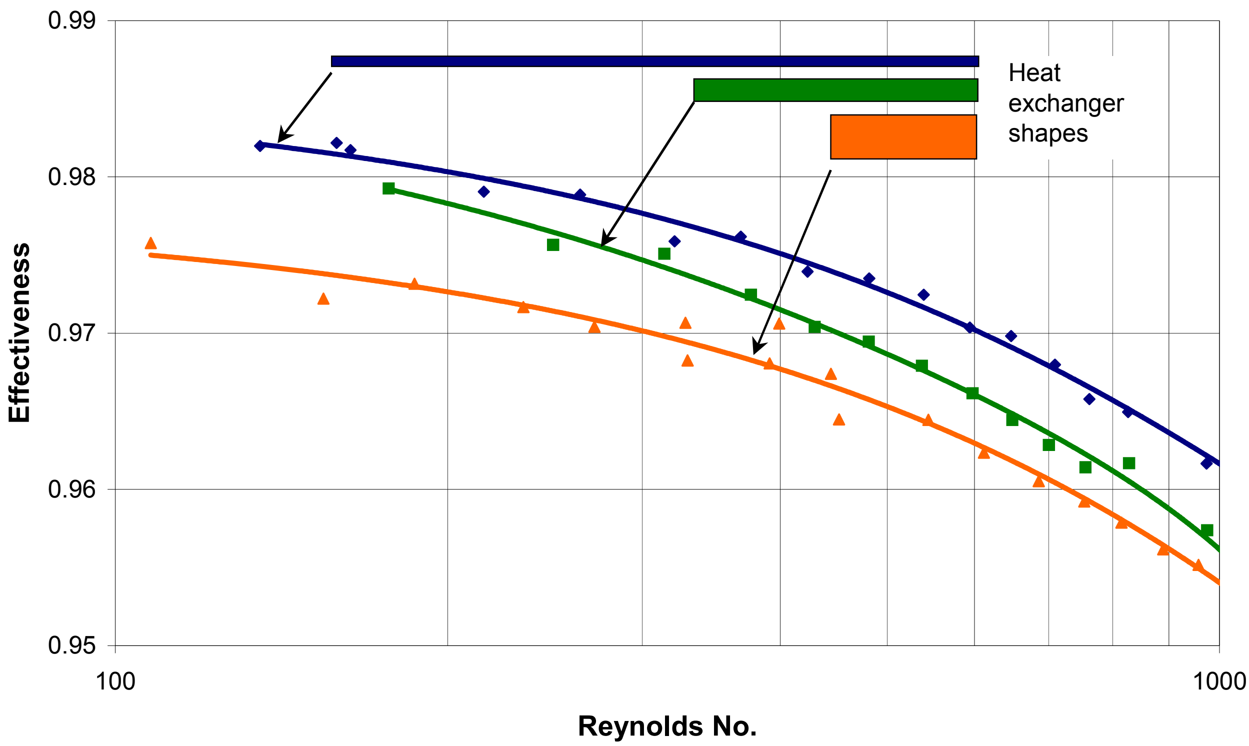

Figure 4: The effect of passage folding on high effectiveness performance of equal area water/water counterflow heat exchangers with heat capacity ratio of 1.

CONCLUSIONS

In the Reynolds Numbers range 100 to 1500, tortuous flow paths can considerably enhance overall heat transfer coefficients for a specified combination of pressure drop and thermal effectiveness, thereby considerably reducing exchanger size over that achievable with fully-developed laminar flow.

Folding of passages to achieve a more satisfactory heat exchanger size envelope is a viable approach even at relatively high heat exchange effectiveness. The detrimental effects may be characterized and appropriate allowance made in the design.

NOMENCLATURE

A	area	m^2
c	specific heat	J/kg K
D_e	equivalent diameter	m
G	mass flux	kg/m^2s
h	heat transfer coefficient	W/m^2K
k	thermal conductivity	W/mK
L	length	m
m	mass flow	kg/s
ΔP	pressure drop	kPa
U	overall heat transfer coeff	W/m^2K
μ	viscosity	mNs/m^2
ρ	density	kg/m^3
f	Fanning friction factor	
j	St $Pr^{2/3}$	
Nu	Nusselt Number, hD_e/k	
NTU	heat transfer unit, UA/mc	
Pr	Prandtl Number, $c\mu/k$	
Re	Reynolds Number, GD_e/μ	
St	Stanton Number, h/Gc	