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Inlet tube spacing and protrusion inlet effects on multiple circular tubes in the laminar, transitional and turbulent flow regimes

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ABSTRACT

The purpose of this study was to investigate inlet tube spacing and protrusion effects on multiple circular tubes in the laminar, transitional and turbulent flow regimes. An experimental set-up was built for this investigation and three configurations of test sections were investigated. The first was a single-tube test section for validation purposes, of which the results were compared with literature. The second was two multi-tube test sections with three tubes spaced at different pitches. The third configuration was similar to configuration two, except that the centre tube had a small protrusion. All the tubes had an inner diameter of 3.97 mm, and long tube lengths of 6 m were used to ensure fully developed flow. The tubes were electrically heated that ensured a constant heat flux heating condition. Water was used as the test fluid, and the Prandtl number varied between 3 and 7. The experiments were conducted at heat fluxes of 2, 3 and 4 kW/m^2 for Reynolds numbers between 1000 and 7000, to ensure that the transitional flow regime, as well as sufficient parts of the laminar and turbulent flow regimes, were covered. The tubes were spaced apart from each other at 1.25, 1.4 and 1.5 times the outer tube diameter, and the protrusion of the centre tube was 10% of the tube inner diameter. It was found that an increased pitch ratio dampened the inlet disturbances in the centre tube and reduced the flow asymmetry in the side tubes, therefore the differences in the critical Reynolds numbers and transition gradients of the three tubes decreased. As the inlet disturbances were damped in the centre tube, transitional was delayed compared to a single tube with a square-edged inlet. For the side tubes, the increased flow asymmetry led to increased critical Reynolds numbers, as well as increased transition gradients. The presence of a protrusion inlet in the centre tube significantly increased the asymmetry of the flow in the side tubes, which led to an additional increase in the critical Reynolds numbers and the transition gradients increased. Free convection effects also led to increased critical Reynolds numbers and transition gradients, as well as decreased differences between the results of the tubes in the multi-tube set-up when a square-edged inlet was used. However, free convection effects were not able to dampen the inlet disturbances caused by a protrusion inlet in the centre tube.

1. Introduction

Flow maldistributions from inlets and the headers into parallel channels typically used in heat exchangers are frequently encountered in heat transfer equipment, such as condensers, boilers, evaporators, solar energy flat plate collectors, air-to-air plate heat exchangers, automobile radiators, fuel cells, microchannel heat exchangers, as well as in nuclear cooling systems. According to the Scopus® abstract and citation database of Elsevier, 710 papers have been published with the keyword "protrusion" in the title. Only 42 of these papers are related to thermal and/or fluid sciences. In most of these papers protrusions were investigated as a heat transfer enhancement mechanism, such as in references [1–7], however, it was not investigated as part of inlet effects.

More than 210 articles were published with the keyword "maldistribution" in the title, more than 380 with the keywords "inlet" and "design", more than 150 with the keywords "inlet" and "geometry", and more than 50 with the three keywords "inlet", "design" and "geometry". Furthermore, more than 390 articles were published with the keywords "entrance" and "effects", and more than 70 with the keywords "entrance" and "design". Of all these papers, only two [8,9] were review papers. The paper of Mueller and Chou [8] is a general review, more applicable to

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Nomenclature

A	area
a	annular diameter ratio
C	constant used in correlations
C_p	constant pressure specific heat
D	inner diameter
D_h	hydraulic diameter
D_o	outer diameter
EB	energy balance
f	friction factor
f_{cr}	friction factor at Re_{cr}
f_{qt}	friction factor at Re_{qt}
Gz	Graetz number
h	heat transfer coefficient
I	current
i	data point index
j	colburn j-factor
j_{cr}	colburn j-factor at Re_{cr}
j_{qt}	colburn j-factor at Re_{qt}
k	thermal conductivity
L	length
L_{FD}	fully developed tube length between pressure taps P1 and P2 in Fig. 3
L_t	thermal entrance length
M	measurement or calculated value
$\dot{m}$	mass flow rate
Nu	Nusselt number
P	pressure
Pr	Prandtl number
$\dot{Q}_e$	electric heat input rate
$\dot{Q}_w$	water heat transfer rate
$\dot{q}$	heat flux
R_{tube}	tube thermal resistance
Re	Reynolds number
Re_{cr}	critical Reynolds number
Re_{qt}	start of quasi-turbulent regime
ΔRe	width of transitional flow regime
T	temperature
t	protrusion distance (Fig. 1(f))
TG_f	transition gradient in terms of friction factor results
TG_j	transition gradient in terms of Colburn j-factor results
V	velocity/voltage
x	distance from inlet

Greek letters

δ	uncertainty
ε	surface roughness
λ	annular geometric parameter
μ	dynamic viscosity
ρ	density

Subscripts

b	bulk
c	cross-section
cor	correlation
exp	experimental
i	inlet
m	mean
o	outer/outlet
s	heat transfer surface

industrial type of heat exchangers (including shell-and-tube heat exchangers), while the paper of Tang et al. [9] focused on microchannels.

The review paper of Mueller and Chou [8] discussed the different types of maldistributions and their causes. Recommendations were given to avoid maldistributions, and it was concluded that although the performance loss in many cases might be small, the associated mechanical problems can be severe. According to Mueller and Chou: "The prefix *mal* means defective or bad, and thus the meaning of the term maldistribution depends on how one defines distribution. If a comparison is made to a uniform distribution, then how is uniform defined? For a tube-side flow through a bundle of tubes, a uniform distribution can mean an equal amount of fluid in each tube (the "normal" definition), or that each particle of fluid has an equal residence time in each tube (this would be "plug" flow)". They also pointed out that for flow across a tube bundle, the definition gets more complex since the local velocities are changing as the fluid flows through the bundle, as well as other factors such as by-passing and leakages.

Mueller and Chou [8] categorized maldistributions into four categories which are: (1) mechanical causes, (2) self-induced maldistribution due to the changing viscosities with heat transfer (especially in laminar flow), and thermoacoustic oscillations in some heat exchangers, (3) two-phase (gas–liquid) heat exchangers in which it is challenging to uniformly distribute all the flow through a tube bundle, and (4) fouling and/or corrosion. Mechanical caused maldistributions were further classified by Mueller and Chou into four subcategories: (1) entry designs which includes entry problems caused by duct, nozzle, and header designs, or the presence of other exchangers, (2) bypass and leakage streams, (3) fabrication tolerances, and (4) shallow bundles.

According to Tang et al. [9], most designers assume that the flow distribution in a multiple tube heat exchanger is uniform, but that this is an incorrect assumption as maldistribution occurs in all types of heat exchangers. Flow maldistribution reduces the thermal performance and increases the pumping power, and maldistribution challenges specifically occur in compact heat exchangers with many small channels in a parallel flow configuration. According to Tang et al. [9], Jiao et al. [10] indicated that flow maldistribution can be classified into two types, namely gross maldistribution and passage-to-passage maldistribution. Gross maldistribution is the result of the improper design of the heat exchanger inlets, while passage-to-passage maldistribution occurs due to manufacturing tolerances, fouling, and frosting of condensable impurities.

Except for the two review papers that were discussed, four more papers on flow maldistributions [11–14] were identified as relevant to this study. Lalot et al. [11] presented a numerical and experimental study of the effect of flow nonuniformity on the performance of heat exchangers. A case study is given where reverse flow may occur for poor inlet header design. A proposal is given to homogenize the flow distribution by adding a uniformly perforated grid in the inlet header. It was shown that a flow nonuniformity at the inlet decreased the effectiveness of condensers and counterflow heat exchangers by approximately 7%, while the decrease was up to 25% for crossflow exchangers.

Wang et al. [12] experimentally and numerically investigated single-phase flow in a compact parallel tube heat exchanger. The inlet and outlet of each tube were from a rectangular header with a square cross-section. The effects of different inlet flow conditions were investigated, which included different tube diameters, header size, area ratio, flow direction (Z and U-type), as well as the effect