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Distribution of air–water mixtures in parallel vertical channels as an effect of the header geometry

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ABSTRACT

Uneven phase distribution in heat exchangers is a cause of severe reductions in thermal performances of refrigeration equipment. To date, no general design rules are available to avoid phase separation in manifolds with several outlet channels, and even predicting the phase and mass distribution in parallel channels is a demanding task. In the present paper, measurements of two-phase air–water distributions are reported with reference to a horizontal header supplying 16 vertical upward channels. The effects of the operating conditions, the header geometry and the inlet port nozzle were investigated in the ranges of liquid and gas superficial velocities of 0.2–1.2 and 1.5–16.5 m/s, respectively. Among the fitting devices used, the insertion of a co-axial, multi-hole distributor inside the header confirmed the possibility of greatly improving the liquid and gas flow distribution by the proper selection of position, diameter and number of the flow openings between the supplying distributor and the system of parallel channels connected to the header.

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1. Introduction

One of the factors that most strongly influence the performance of compact heat exchangers is the degree of flow rate uniformity in the parallel channels where the heat transfer occurs.

Plate heat exchangers (PHE) have long been used in a wide range of industrial applications regarding single-phase flow. Recently, two-phase gas/liquid mixtures have been utilised in such exchangers in processes involving vaporisation and condensation. Typical examples include refrigerating cycles, in which the use of such components favours compactness and enhances heat transfer. Multi-micro-channel tube heat exchangers are also quite common, especially in automotive air-conditioning applications. Interest in micro-channel heat exchangers is keen, owing to their compactness, which saves space, weight and refrigerant charge.

In such applications, the problem of ensuring uniform phase distribution in the multi-channel system where heat transfer occurs concerns both evaporators and condensers. Uneven two-phase distribution can occur either inside each channel, owing to the asymmetrical parallel and diagonal flow, or inside the header, owing to the separation of the two-phase mixture in the header-tube junctions.

Flow maldistribution in heat exchangers may be spatial, temporal or both, its effect being to reduce both thermal and fluid dynamic performances. Many papers have dealt with the effects of flow maldistribution on the performance of heat exchangers (Mueller [1]; Mueller and Chiou [2]; Probhakara Rao et al. [3]). Some maldistributions are the result of fabrication conditions, such as mechanical design or manufacturing tolerances; others are caused by the heat transfer and fluid flow process itself, by fouling and/or corrosion, or by the typical non-uniformities of two-phase flows. While some cases of maldistribution have little influence on heat exchanger performance, other cases result in significant loss of performance and/or mechanical failure of the devices (Mueller and Chiou [2]). For these reasons, several recent studies have analysed the effects of geometrical configuration and operating conditions on the distribution of two-phase flows in parallel channels, with or without heat transfer.

Most studies on two-phase distribution in compact heat exchangers have been carried out on the experimental side. Generally speaking, experiments have been performed under adiabatic conditions. Only Vist and Pettersen [4] have investigated the influence of changing the heat flux to the evaporator tubes on the two-phase distribution in the manifold. Changing the heat load on the evaporator test section had little influence on the two-phase flow distribution, while the two-phase flow distribution markedly influenced the heat transfer between the refrigerant and the counter-flowing water. All literature studies consider air–water mixtures or halocarbon refrigerants. Rong et al. [5] used air–water mixtures to simulate an R-134a refrigerant system at the same inlet volumetric flow rates. Webb and Chung [6] simulated the actual refrigerant flow conditions by means of air–water mixtures with the

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Nomenclature

d	orifice nozzle diameter [m]
D	pipe diameter [m]
d_f	hole diameter of the inner distributor [m]
N	number of channel pairs [-]
$\dot{m}_g$	gas flow rate [kg/s]
$\dot{m}_l$	liquid flow rate [kg/s]
STD_g	gas standard deviation [-]
STD_l	liquid standard deviation [-]
V_{SG}	gas superficial velocity [m/s]
V_{SL}	liquid superficial velocity [m/s]
Greek letters	
β	angular position of the inner distributor [°]
δ	orifices diameter (header–channel connection) [m]
σ	area restriction ($\sigma = (d/D)^2$) [-]

same liquid–vapour density ratio and the same Martinelli parameters (X_{tt}). Operating conditions varied from bubbly and slug flows (Osakabe et al. [7]; Horiki and Osakabe [8]) to annular flow (Lee and Lee [9], Kim and Han [10]) at the header inlet.

Lee recently presented an extensive review [11] of two-phase distribution studies in dividing tubes and parallel channels. A review of experimental and theoretical investigations was also presented by Guglielmini [12]. The effects of tube outlet direction, tube protrusion depth, mass flow rate and quality were experimentally investigated by Kim and Sin [13] for a horizontal round header and 30 vertical flat tubes simulating a parallel flow heat exchanger in which the flow could be in the upward or downward direction. Kim and Han [10] recently extended their experimentation to a header with a small number (i.e. 10) of branching flat tubes. For flush-mounted configurations (i.e. no protrusions), their results confirmed what other researchers had found: downward flow and upward flow caused water to flow mostly through the front and rear parts of the header, respectively. The effect of tube protrusion depth was also studied: for the downward flow configuration, more water was forced to the rear part of the header as protrusion depth increased, while for the upward flow configuration, the flow distribution was not significantly altered.

Ahmad et al. [14] investigated the flow distribution of HFE 7100 from a short header (127 mm) feeding eight rectangular channels (hydraulic diameter 4 mm) in different flow orientations and flow patterns, including stratified and annular flows. They concluded that the vertical upward channel configuration yielded the worst mass distribution in the parallel pipes. These authors proposed the use of a concave perforated plate ("splashing grid") at the header inlet to homogenise the flow distribution at the parallel channel inlet: the improvements in flow uniformity can be ascribed, according to the authors, to a multidirectional effect introduced by their fitting.

Experiments on two-phase flow distribution have demonstrated that, among the main factors affecting the separation of the phases, a very important role is played by the various geometric factors involved. These include: distributor shape and size, channel-junction shape, header and channel orientation, presence of orifices and nozzles, size and length of the inlet pipe, and the intrusion depth of the channels into the header wall. However, the behaviour can be completely changed by particular upstream conditions, such as the presence of fittings (e.g. nozzles or short inlet tubes), which are able to modify the two-phase flow pattern at the inlet of the manifold and inside the header. As Webb and Chung [6] concluded, the design of devices to improve the distribution is nowadays "highly empirical".

Although orifices and nozzles are commonly used by heat exchanger manufacturers to empirically adjust the flow rate distribution on the basis of the operating conditions and of the unit dimension, these aspects have not yet been sufficiently investigated, and no systematic study is reported in the literature.

The present paper reports the results of several experiments carried out on a horizontal header supplying 16 upwardly oriented vertical channels. The aim of the experimental campaign was to investigate some phenomenological aspects of the two-phase flow separation produced by a series of fittings able to affect the flow distribution downstream of the header. In a previous paper (Marchitto et al. [15]) the influence of upstream orifice plates and perforated plate diameters have been investigated and discussed. In the present paper the attention is mainly focused on forcing the flow inside the header to change its main direction, as an effect of an in-line perforated distributor inserted coaxially to the header itself.

2. Experiments

Experiments were carried out on a simple test section in order to investigate some phenomenological aspects of two-phase distribution in compact heat exchanger manifolds and the effect of several fittings: upstream, downstream and inside the header. The flow inside the vertical channels was upward.

The test section was designed in such a way as to allow the flow structure in the inlet port, inside the header and along the parallel channels to be observed visually. The instrumentation was designed to record the evolution of pressure and void fraction inside the header and to measure the liquid and gas flow rates insides the parallel channels, downstream of the header. Video recordings were made in order to infer the flow patterns inside the distributor during intermittent and quasi-annular flows.

2.1. Experimental set-up and procedure

This experimental apparatus consists of a transparent test section and two supply lines of air and water that converge into a horizontal pipe. Phase mixing (through a T fitting) allows intermittent and annular flow regimes to be generated. Downstream of the mixer, the mixture flows horizontally inside a 2.0 m long acrylic pipe with an inner diameter of 26 mm. The pipe is connected by a flange to the inlet port of the test section, which is also made of acrylic. An overall sketch of the experimental apparatus is shown in Fig. 1.

The test section (Fig. 2) consists of a horizontal header, an interchangeable orifice plate at the header inlet and a system of 16 vertical channels, of rectangular cross-section. The header has a circular cross-section of with an inner diameter (D) of 26 mm and is machined and polished from a rectangular block of acrylic resin. The transparent block facilitates visualisation, while the flat external surface minimises the distortion due to refraction. The header is equipped with an interchangeable plate (hereafter: perforated plate) with 16 orifices supplying the vertical channels, which are connected to the header with a pitch of 18 mm. The channel dimensions (length, depth, width) are 500, 15 and 18 mm, respectively. The perforated plate has pass-through hole dimensions of 3 mm (diameter δ) and 6 mm (plate thickness).

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