THE EFFECT OF FLOW DISTRIBUTION IN PARALLEL CHANNELS OF COUNTERFLOW HEAT EXCHANGERS

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INTRODUCTION

It has long been known that poor flow distribution in parallel channels causes a degradation in heat exchanger performance. Examples of this can be found in air liquefaction plants, where the gradual plugging of a few of the tubes in a parallel array reduces performance of the plant, not only because of the increased pressure drop, but also because of a reduction in the thermal effectiveness of the exchangers. As this paper will illustrate, the reduction in performance can be particularly severe in balanced flow cryogenic heat exchangers of very high thermal effectiveness.

The problem of predicting performance as a function of flow distribution cannot be solved completely because of the infinite number of ways the flow can distribute itself in a set of parallel channels. The purpose of this paper is to predict performance degradation in some very simple cases of maldistribution, so that starting with predictions of flow distribution, rough estimates of performance can be made.

There is some prior work in predicting the effect of header design on flow distribution [1-3]. However, there appears to be only very little work in relating this flow distribution to exchanger performance. The reason for this is probably that the reduction in performance of the usual low-effectiveness exchanger is generally not serious. For example, McDonald and Eng [4] studied the case of nonuniform distribution of tube side flow in single pass cross-flow exchangers by means of analog computation. They concluded that for exchangers of $N_{tu}$ below about four, the effect of even large nonuniformities was negligible. Cichelli and Boucher [3] indicated only small changes in performance resulting from large nonuniformities on the tube side, for counterflow shell-and-tube exchangers of small $N_{tu}$, with the shell-side fluid continuously mixed.

In the present paper, three simple cases will be studied. In all three cases, the following assumptions will be made:

1. All channels are in pure counterflow (effects such as longitudinal conduction which would cause deviation from counterflow performance are assumed negligible).

2. One side of the exchanger (called the “uniform” side) has flow distributed uniformly among all its channels. The other side (the “nonuniform” side) carries a lower-than-average flow in each channel, uniformly distributed in a fraction
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$F_L$ of the total channels, and carries a higher-than-average flow in each channel, uniformly distributed among the remaining fraction $(1 - F_L)$ of the total channels (see Fig. 1).

3. There is a balanced flow condition between the two sides of the heat exchanger. That is, the total flow rates on each side are equal, and the specific heats on each side are equal and constant throughout the exchanger.

4. The product $UA$ for a given exchanger does not vary with flow rate on the nonuniform side; that is, $UA$ is the same in those tubes carrying higher-than-average flow as in those tubes carrying lower-than-average flow. This condition would exist in the case of fully-developed laminar flow—where the heat transfer coefficient is independent of velocity—or in the case where the uniform-side thermal resistance predominates over the nonuniform side.

**CASE I. PAIRED CHANNELS**

In this case, each channel of one side of the exchanger is paired (in heat transfer contact) with a single channel on the other side of the exchanger for the whole length of the exchanger. An example of this case would be a number of Joy-Collins exchangers [5], or similar exchangers, in a parallel array. A purely counterflow tube-in-shell exchanger or a plate-fin exchanger almost fits into this category, but in these latter two cases the channels are not paired strictly on a one-to-one basis, but rather, each channel may exchange heat with more than one channel on the other side.

The temperature distribution resulting from the arrangement of Case I is illustrated in Fig. 2. In this figure, the uniform side is shown as the cold side and the nonuniform side as the hot side. There are two separate temperature distributions on each side of the exchanger: one distribution corresponding to those channel pairs with higher-than-average flows on the nonuniform side and one corresponding to those pairs with lower-than-average flows on the nonuniform side. At the outlet of each side, fluid of two different temperature levels must mix, resulting in an inefficiency due to the entropy of mixing. In addition to this mixing inefficiency, it can be shown that the mean temperature difference between streams is smaller with this nonuniform distribution than with a uniform distribution on both sides. This results in the necessity of a larger exchanger to do the same job of heat transfer.

The problem is solved here by first considering a single pair of tubes with higher-than-average flow on, say, the hot side, and then considering another pair of tubes.