

Review

Review of internal cooling augmentation using baffles

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Heat transfer augmentation techniques refer to different methods used to increase rate of heat transfer without affecting much overall performance of the system. These techniques are used in heat exchangers. Like ribs, jet impingement and other passive heat transfer enhancement methods, insertion of baffle in a cooling system has been used for various types of industrial applications such as internal cooling systems of gas turbine blades, electronic cooling devices, shell and tube type heat exchangers, thermal regenerators and labyrinth seals for turbo-machines. These techniques broadly are of three types namely: passive, active and compound techniques. This paper reviews the internal cooling augmentation using different type of baffles.

Key words: Heat transfer augmentation technique, baffles, active method, passive method, compound method.

INTRODUCTION

Generally, heat transfer augmentation techniques are classified in three broad categories:

Active method

This method involves some external power input for the enhancement of heat transfer; some examples of active methods include induced pulsation by cams and reciprocating plungers, the use of a magnetic field to disturb the seeded light particles in a flowing stream, etc.

Passive method

These methods generally use surface or geometrical modifications to the flow channel by incorporating inserts or additional devices. For example, use of inserts, use of rough surfaces etc.

Compound method

This is the combination of the aforementioned two

methods.

PASSIVE HEAT TRANSFER AUGMENTATION METHODS

Passive heat transfer augmentation methods as stated earlier does not need any external power input. In the convective heat transfer one of the ways to enhance heat transfer rate is to increase the effective surface area and residence time of the heat transfer fluids. The passive methods are based on the same principle. Use of this technique causes the swirl in the bulk of the fluids and disturbs the actual boundary layer so as to increase effective surface area, residence time and consequently heat transfer coefficient in existing system. The following methods are used generally used:

- 1) Inserts
- 2) Extended surface
- 3) Surface modifications
- 4) Use of additives

INSERTS

Inserts refer to the additional arrangements made as an obstacle to fluid flow so as to augment heat transfer as

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explained earlier. Different types of inserts are:

- 1) Twisted tape and wire coils.
- 2) Ribs, baffles and plates.

This paper contributes for review of baffles.

BAFFLES

There are several techniques available to enhance the heat transfer coefficient of gases in internal cooling. One of the common internal cooling enhances techniques is the placement of internal flow swirls, tape twistors or baffles. The swirl insert and tape twister techniques create a significant amount of bulk flow disturbance, and the pressure drop penalties are much higher compared to the gain in heat transfer coefficient. Baffles also create bulk flow disturbance, but unlike tapes or swirls, baffles are discrete objects. Therefore, the flow disturbance created by baffles may be localized, but more intense. Usually the baffle plate is attached to the thermally active surface to augment heat transfer by providing additional fin-link surface area for heat transfer and better mixing.

Use of baffles

The main roles of a baffle in a shell and tube heat exchanger are:

- i) Hold tubes in position (preventing sagging), both in production and operation.
- ii) Prevent the effects of vibration which is increased with both fluid velocity and the length of the exchanger.
- iii) Direct shell-side fluid flow along tube field. This increases fluid velocity and the effective heat-transfer coefficient of the exchanger.

In a static mixer, baffles are used to promote mixing. In a chemical reactor, baffles are often attached to the interior walls to promote mixing and thus increase heat transfer and possibly chemical reaction rates.

Types of baffles

Implementation of baffles is decided on the basis of size, cost and their ability to lend support to the tube bundles and direct flow. Often this is linked to available pressure drop and the size and number of passes within the exchanger. Special allowances/changes are also made for finned tubes. The different types of baffles include:

- i) Segmental baffles (of which single segment is the most common).
- ii) Rod or bar baffles (giving a uniform shell-side flow).
- iii) Helical baffles (similar to segmental with less pressure drop for same size exchanger).

- iv) Longitudinal flow baffles (used in a two-pass shell).
- v) Impingement baffles (used for protecting bundle when entrance velocity is high).
- vi) Orifice baffles.

Installation of baffles

Baffles deal with the concern of support and fluid direction in heat exchangers. In this way it is vital that they are spaced correctly at installation. The minimum baffle spacing is the greater of 50 mm or one fifth of the inner shell diameter. The maximum baffle spacing is dependent on material and size of tubes. The Tubular Exchanger Manufacturers Association sets out guidelines. There are also segments with a "no tubes in window" design that affects the acceptable spacing within the design. An important design consideration is that no recirculation zones or dead spots form - both of which are counterproductive to effective heat transfer. Some of the common "baffle configurations" are shown in Figures 1 to 4. Examples of baffle installation are shown in Figures 5 to 6.

REVIEW OF WORK CARRIED OUT

Dutta et al. (2004) investigated the local heat transfer characteristics and the associated frictional head loss in a rectangular channel with inclined solid and perforated baffles. The main objective of the study was to augment both local and global heat transfer behavior of a gaseous fluid (air) by placement of two inclined baffles. Since the flow disturbances and wakes generated by the upstream inclined baffle can potentially affect the performance of the downstream baffle, an average heat transfer performance is considered to cover the entire heated length. The local Nusselt number ratio with two inclined baffles significantly depends on the arrangement (orientation, perforation, and position of the baffles) used. Two inclined baffles augment the local heat transfer coefficient for a longer region of interest. The overall heat transfer coefficient is much higher with two inclined baffles than that with a single baffle placed in the same channel. The average Nusselt number can be as high as 5.0 times the average Nusselt number of a smooth channel. Localized high heat flux zones can be effectively cooled with properly designed perforated baffles in those regions. The local Nusselt number ratio is not a strong function of flow Reynolds number. However, in a particular arrangement the friction factor ratio increases with increase in the flow Reynolds number. For two inclined baffle cases, the frictional head loss is much higher than that of a single baffle arrangement. Moreover, in two baffle cases the friction factor ratio is larger if the second baffle is attached to the bottom plate instead of the top heated surface. Pulvirenti et al. (2010) experimentally studied on saturated flow boiling heat



Figure 1. Perforated baffles.

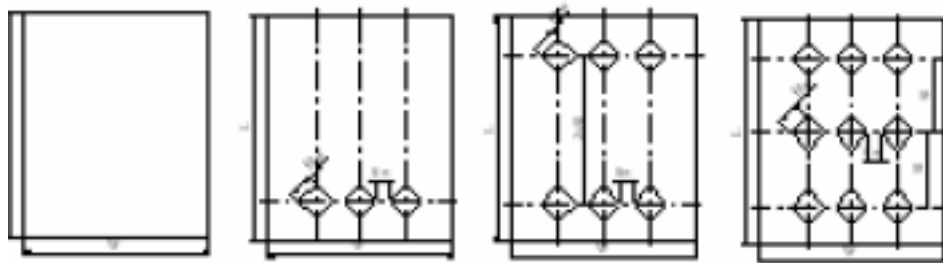


Figure 2. Baffle plate configuration.



Figure 3. Porous baffle.



Figure 4. Solid baffles.

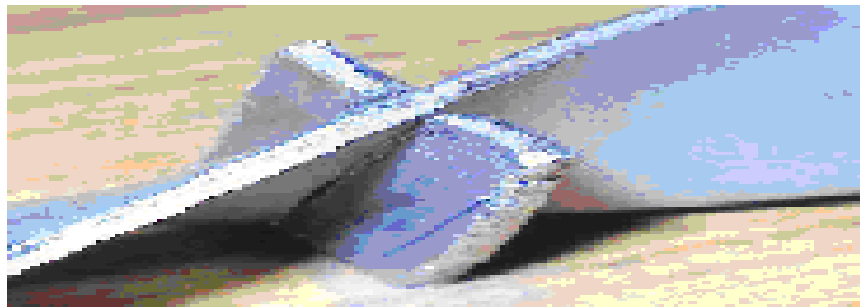


Figure 5. Tape with attached baffle.



Figure 6. Baffles in rectangular duct.

transfer of HFE-7100 in vertical rectangular channels with offset strip fins was presented. The experiments had been carried out at atmospheric pressure, over a wide range of vapour quality and heat fluxes up to $1.8 \times 10 \text{ W/m}^2$. The local boiling heat transfer coefficient has been obtained from experiments and analyzed by means of Chen superposition method. In the present study, experimental investigations have been performed to analyze the flow boiling heat transfer of HFE-7100 in vertical rectangular channels with offset strip fins. Two different regimes have been detected.

The first is convective boiling regime, where heat transfer coefficient depends on quality and mass flux but is independent of heat flux. Under this regime, the correlation found by Feldman et al. (2000), together with as hoc single-phase Colburn factor, give a good agreement with our experimental results. The second is nucleate boiling regime, with high heat flux, where the heat transfer coefficient depends on heat flux but is independent of quality and mass flux. Under this regime, correlations found by Kim and Sohn (2006) gives a good agreement with these experimental results. Warriar et al. (2002) performed experiments with the channels oriented horizontally and uniform heat fluxes applied at the top and bottom surfaces. The parameters that were varied during the experiments include the mass flow rate, inlet liquid sub cooling, and heat flux. Additionally, in these experiments, the single and two-phase pressure drop across the channels was also measured. A correlation has been developed for two-phase flow pressure drop under sub cooled and saturated nucleate boiling conditions. Furthermore, two new correlations are proposed one for sub cooled flow boiling heat transfer and the other for saturated flow boiling heat transfer.

Single-phase forced convection

The variation of Nusselt No. for single-phase forced convection as a function of the axial distance. The numerical results in the textbook by Kays and Crawford (1993); similar results were obtained for all the other test cases. It can be seen that the measured values agree quite well with the numerical results, especially near the fully developed region. A comparison of the measured single-phase pressure drop with that predicated for laminar flow in rectangular channels. The fanning friction factor used in predicting the pressure drop was $f = 17.25/\text{Reynold No.}$ It was seen that there is good agreement between the experimentally measured and analytically predicted values, especially at lower mass fluxes.

Two-phase pressure drop

The two-phase flow conditions in the channel were assumed to exist downstream of the location where onset

of nucleate boiling was observed to occur. The location for onset of nucleate boiling was established as the location where a large increase in the heat transfer coefficient beyond the single-phase value was observed. Aroon et al. (2006) numerically predicted the hydrodynamic and thermally developed turbulent flow for a stationary duct with square ribs aligned normal to the main flow direction. The capability of the detached eddy simulation (DES) version of the 1988 k-w model has been validated in predicting the turbulent flow field and the heat transfer in a complete two pass channel. Results of mean flow quantities, secondary flows, friction and heat transfer were compared with experiments and large-eddy simulations (LES). In the current study, detached eddy simulation (DES) is carried out in a complete two-pass channel with 12 ribs in the first and second passes, connected by a 180° bend. The flow in the first pass of the duct is compared with LES computations by Sewall and Tafti (2004a). Experiments by Rau et al. (1988), the flow in the 180° bend is compared with LES results in the bend by Sewall and Tafti (2005) and experimental results by Nan et al. (1988) and Sewall et al. (?) all physical phenomena characterized by mean and turbulent rms quantities were reproduced with excellent quantitative accuracy. Byongjoo et al. (2006) experimentally studied on saturated flow boiling heat transfer of R113 was performed in a vertical rectangular channel with offset strip fins. Two-phase pressure gradients and boiling heat transfer coefficients in an electrically heated test section were measured for the quality range of 0 to 0.6, mass flux range of 17 to 43 kg/m^2 .

Two-phase frictional multiplier was determined as a function of marginally parameter. A superposition method for the flow boiling heat transfer coefficient that included the contribution of saturated nucleate boiling was verified also for flow boiling in a channel with offset strip fins. Two-phase frictional multiplier and the local boiling heat transfer coefficients were measured and correlated. Measured values of two-phase frictional multiplier in a channel with offset strip fins were higher by as much as 80% than those in round tubes. Kang-Hoon et al. (2003) carried out experiment to measure module average heat transfer coefficients in uniformly heated rectangular channel with wall mounted porous baffles. Baffles were mounted alternatively on top and bottom of the walls. Heat transfer coefficients and pressure loss for periodically fully developed flow and heat transfer were obtained for different types of porous medium (10, 20 and 40 pores per inch) with two window cut ratios and two baffles thickness to channel hydraulic diameter ratios. The experimental procedure was validated by comparing the data for the straight channel with no baffles with those in the literature [Publications in Engineering, vol. 2, University of California, Berkeley, 1930, 443, Int. Chem. Eng. 16(1976): 359. The use of porous baffles resulted in heat transfer enhancement as high as 300% compared to heat transfer in straight channel with no baffles.

Experimental procedure was validated by making heat transfer measurements for flow through a straight channel without any baffles. The variation of average Nusselt number with Reynolds number for fully developed flow in straight channels. Experimental data is compared against the correlations available in the literature. The average Nusselt number for fully developed flow in a straight channel was compared with results obtained from correlation of Gnielinski (1976) and Dittus-Boelter (1930). The maximum difference for average Nusselt number obtained in the present work and those correlations in the literature of Dittus-Boelter (1930) and Gnielinski (1976) is 5.9%.

Won et al. (2003) experimentally investigated spatially-resolved, local flow structure and surface Nusselt numbers presented for a stationary channel with an aspect ratio of 4 and angled rib tabulators inclined at 45° with perpendicular orientations on two opposite surfaces. Instantaneous flow visualizations and time-averaged flow structural data show a variety of flow phenomena, including the development of increased numbers of multiple, smaller vortex pairs as the Reynolds number increases, strong span wise secondary flow components, which move in opposite directions in the top and bottom halves of the channel, and result in the formation of other secondary flows and vertical motions. The flow structure results include time-averaged distributions of local stream wise vorticity, different components of local velocity, local total pressure, local static pressure, and secondary flow vectors, as well as instantaneous flow visualization images. Flow visualizations show that increased numbers of multiple, smaller vortex pairs develop in the channel as the Reynolds number increases, which implies that energetic flow structures with a wide range of length scales are present in the fully turbulent channel flow and indicates significant augmentations of local surface heat transfer rates. Tsay et al. (2005) numerically investigated the heat transfer enhancement on a vertical baffle in backward facing step flow channel. The effect of the baffle height, thickness and the distance between the baffle and the backward facing step on the flow was studied. They found that an insertion of a baffle into the flow could increase the average Nusselt number by 190%. They also observed that the flow conditions and heat transfer characteristics are strong function of the baffle position.

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