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Intensification of Heat Transfer Processes

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New challenges in efficient heat recuperation arise when integrating renewables, polygeneration and combined heat and power (CHP) units with traditional sources of heat in industry and the communal sector, as it is shown by Klemeš et al. (2010). Heat transfer enhancement is an efficient technique to increase energy saving when retrofitting heat exchangers or designing a new heat transfer system. By implementing intensified techniques in existing exchangers, higher heat transfer coefficients can be achieved, leading to higher heat exchange duties allowing a reduced size of heat transfer equipment and the associated benefits (especially improving heat transfer performance). Intensification techniques provide: (i) Reduction in size of a heat exchanger for a given duty; (ii) Increase in capacity of an existing heat exchanger; (iii) Reduction in approach temperature difference; or (iv) Reduction in pumping power. Conventional enhancement techniques include tube-side enhancements (i.e. enhanced surface tubes, internal tube fins, coatings, fluid additives, mechanical mixing devices, twisted-tape inserts, coiled-wire inserts, etc.); shell-side enhancements (i.e. externally enhanced surface tubes, external tube fins, coatings, fluid additives, helical baffles, etc.). The compact heat exchangers such as tube-fin, plate-fin and plate heat exchangers are using heat transfer intensification and offer significant reduction in size, weight and cost of heat recuperation equipment. Developments in mini- and micro- channel heat exchangers are offering new possibilities of heat transfer intensification in channels of very small hydraulic diameters. Recently such intensification has been widely studied in the process industry from the point of view of individual heat exchangers. Combining several enhancement techniques can achieve higher energy savings when compare to implementing a single technique. It is difficult to identify which intensification technique is more suitable in a certain design, or which combinations of enhancement techniques are expected to contribute the most in compound augmentation applications. This work will survey current practices and review recent advances in enhancement techniques from an economic and performance standpoint.

1. Introduction

Recently, the study of enhanced heat transfer has received a good deal of attention due to increased demands by industry for heat exchange equipment that is less expensive to build and operate. Savings in materials and energy use provides a strong motivation for the development of improved methods of enhancement. Additional motivation is discussed by Reay (2008) where he states that "between 1900 and 1955 the average rate of global energy use rose from about 1 TW to 2 TW. Between 1955 and 1999 energy use rose from 2 TW to about 12 TW, and to 2006 a further 16 % growth in primary energy use was recorded world-wide." Government legislation and specific energy conservation targets have been set for overall energy reduction on a national basis by many countries. Additionally, government incentives are available to reduce energy usage and environmental impact. Gough (2012) points out that the recent nuclear disaster in Japan has prompted the Japanese government to take a more active role in its serious drive to reduce energy use. Recently, additional countries have also started to adopt that approach, making the development of enhanced heat transfer even more important. Reay (2008) notes "that there is a need to reduce CO_2 emissions by over 50 % in order to stabilise their impact on global warming. One way in which we can address this is by judicious use of process intensification technology." He goes on to define process intensification as ''Any engineering development that leads to a substantially smaller,

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cleaner, safer and more energy-efficient technology." It is most often characterised by a huge reduction in plant volume (orders of magnitude); in addition its contribution in reducing greenhouse gas emissions may also be significant.
When designing cooling systems in the transportation and aerospace industries it is imperative that the heat exchangers are compact and lightweight. Additionally, heat transfer enhancement is necessary for many applications found in power plants, chemical, and oil/gas industries. This has led to the development of enhanced heat transfer surfaces. In general, enhanced heat transfer surfaces can be used to: (i) reduce the overall volume of the heat exchanger and to make the heat exchangers more compact and lightweight, (iii) reduce the pumping power required (iii) increase the overall *UA* value of the heat exchanger (where *U* is the overall heat transfer coefficient and *A* is the heat transfer area) (iv) reduce the initial cost of the heat exchanger. *A* higher *UA* value can obtain an increased heat exchange rate for fixed fluid inlet temperatures; or reduce the mean temperature difference for the heat exchanger (increasing the thermodynamic process efficiency and saving operating costs).

Figure 1: Outside Enhanced Surface Micro Fin Tube

(a) (b)

Figure 2: Twisted Tape Tube Inserts (a) plain surface (b) enhanced surface

Enhancement techniques can be separated into two categories: passive and active. Passive methods require no direct application of external power to increase heat transfer, they employ special surface geometries or fluid additives which cause heat transfer enhancement. Active methods require external power for operation. The majority of commercial enhancement techniques are passive ones since commercial active techniques are costly and some have operational problems. Passive techniques provide enhancement by establishing a higher *hA* per unit base surface area (where *h* is the heat transfer coefficient and *A* is the heat transfer surface area). They are utilized by: (i) Increasing the effective heat transfer surface area without appreciably changing the heat transfer coefficient (ii) Increasing the heat transfer coefficient without appreciably changing the surface area. This is typically accomplished by using enhanced heat transfer surfaces which provides mixing due to secondary flows and boundary-layer separation within the channel (see Figure 1). Twisted tapes also increase the heat transfer coefficient without a significant surface area increase by creating vortices that exchange fluid between the wall and core regions of the flow, resulting in an increased heat transfer (iii) Increasing both the heat transfer coefficient and the surface area. These surfaces increase the effective surface area, and enhance heat transfer through repeated growth and destruction of the boundary layers. Kukulka et al. (2013) studied these types of enhancement in detail. This type of surface is illustrated in Figure 3. The 1EHT enhanced heat transfer tube developed by Vipertex, is a novel kind of tube that was developed by modifying surface geometries (i.e. creating a modified surface that is a combination of larger dimples and smaller petals) which can enhance the heat transfer coefficient on both the inside and outside surface of the tube; its details are shown in Figure 3. The 1EHT enhanced heat transfer tube is neither a classic ‘‘integral roughness’’ (little surface area increase) tube, nor an internally finned tube (surface area increase with no flow separation). It can be considered to be more of a hybrid surface that increases surface area and produces flow separation from the dimpled protrusions on the tube. Enhancement of the heat transfer using the 1EHT tube is produced from a combination of increased turbulence, disruption of the boundary layer, secondary flow generation, increased heat transfer surface area and the creation of a large number nucleation sites; all leading to an enhanced heat transfer performance for a wide range of conditions.

(a)

(b)

Figure 3: Enhanced Heat Transfer Tube (a) Cross Sectional View (b) Outer Surface Detail of the 1EHT Enhanced Tube

When looking at a special surface geometry to enhance heat transfer in an industrial heat exchange application there are various options to consider. In order to compare the performance improvement produced by the various enhanced surfaces designs a comparison of the relative heat transfer performance is made for each enhanced surface. An additional consideration is the increased pressure drop. Sometimes, the benefits gained from heat transfer enhancement are not great enough to offset the increased friction losses. The performance goal is to gain maximum enhancement of heat transfer with a minimum penalty on pumping power.
Compound techniques are also an enhancement method worthwhile considering. Usually the heat transfer coefficient increase is greater than each of the techniques acting alone. Some examples include an enhanced surface tube with a twisted tape insert, a rib-roughened channel with a longitudinal vortex generation, enhanced surface tube with fins (See Figure 4), etc.

Figure 4: Compound Heat Transfer Enhancement using and Enhanced Surface Tube and Extended Surface Fins

Further prospects of heat transfer intensification emerged with the change from the traditional tubular form of heat transfer surface to enhanced surfaces made from a thin sheet metal and combined to form a plate heat exchangers (PHEs). The principles of their construction, operation and design methods are sufficiently well described in literature, see Wang et al. (2007). The channels of the PHE are formed using corrugated plates stamped from thin sheet metal, schematically shown in Figure 5. Two adjacent plates have multiple contact points, as shown in Figure 6, which enable the resulting rigid construction to withstand a high pressure difference between the heat exchanging streams. The channels between the plates have a complex and intricate geometry which creates high levels of turbulence. This is true even at low Reynolds numbers (down to Re values of less than 200). Thermal and hydraulic performance of PHEs is determined by the form of the corrugations and to a great extent by the angle, β, of the corrugations to the flow direction. Hydraulic diameter of the channels can be as small as 3 mm, producing a very compact heat exchanger and enabling an increase in its efficiency.

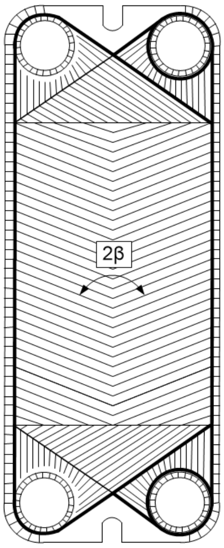

Figure 5: Schematic drawing of a PHE plate

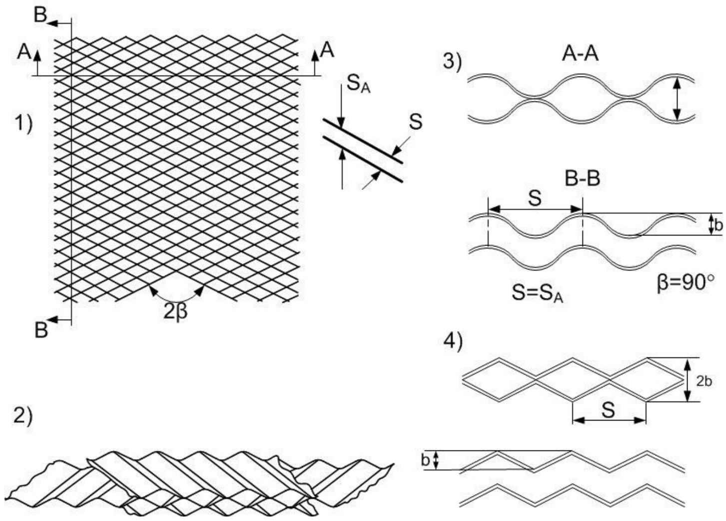

Figure 6: Different corrugation forms used in a PHE: (1, 2) demonstrates the intersection of the adjacent plates; (3) shows channel cross sections for various methods of combining the sinusoidal form of corrugations; (4) shows channel cross sections for various methods of combining the triangular form of corrugations

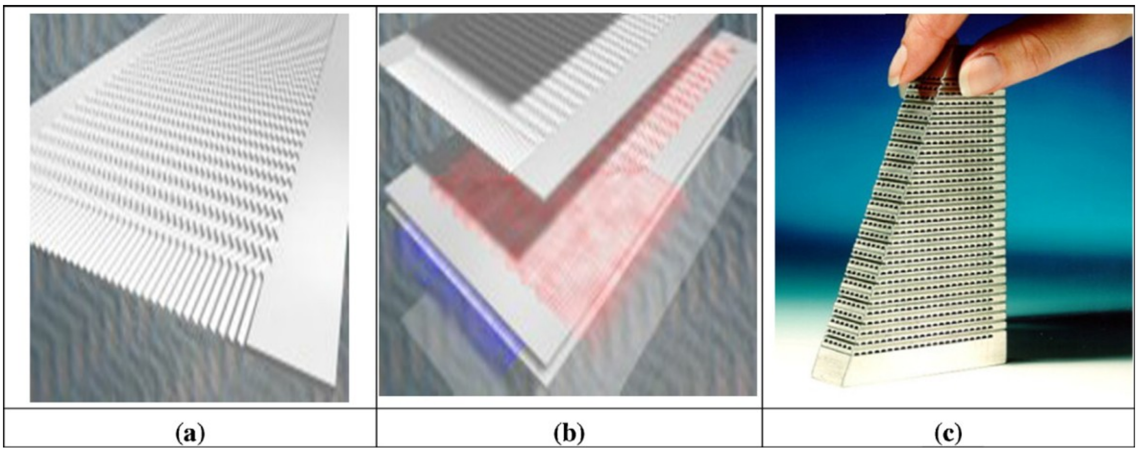

Figure 7: Illustration of PCHE Fabrication (a) plate passages (etched plate), (b) diffusion bonding of plates (stacked plates), (c) final diffusion bonded PCHE section (from Sabharwall et al. 2014 and later Heatric, 2015)

Decreasing the hydraulic diameter in minichannel and microchannel heat exchangers further increases in the compactness of heat transfer surfaces and increases the intensity of heat transfer. As discussed by Kandlikar et al. (2014) this is even apparent in laminar flow regimes. An example of a minichannel heat exchanger is shown in Figure 7. It shows the stages of fabrication of a Printed Circuit Heat Exchanger (PCHE) with minichannels having a hydraulic diameter that is less than 1 mm.

2. Results

Enhanced heat transfer surfaces are important options to be considered in the design of high efficiency systems. These surfaces can be used in a variety of conditions. As an example, the outside enhanced microfin tube (shown in Figure 1) presents a significant heat transfer enhancement when using R410A on smooth and enhanced tubes. For a mass flux range in the range of 10 to 15 kg m^{-2} s^{-1}, the outside evaporation heat transfer coefficient enhancement ratio (when compared to a smooth tube) was approximately 2.2 In another example, the Vipertex 1EHT enhanced tube (see Figure 3) showed outstanding thermal performance characteristics in the traditional laminar flow regime (Re ≤ 2,200) for single phase, inside fluid cooling conditions. The heat transfer enhancement for Re values near 900 is more than five times greater than the heat transfer of a smooth tube at the same conditions (Kukulka et al., 2013). Although the underlying phenomena giving rise to it are not fully understood, this peculiar performance characteristic has been verified as being repeatable for the test fluid, tube geometry, and flow conditions considered. At higher flows there is an approximate two fold increase in heat transfer when compared to smooth tubes under inside fluid cooling conditions.

In the channels of PHEs the heat transfer intensification mechanism is different than in tubes, this is especially evident for tubes with artificial roughness. According to experimental results and generalizing correlations (see Arsenyeva et al., 2012), when compared to smooth tubes at the same Reynolds number, the increase of the friction factor in the channels of the PHEs can be from 10 to 100 times higher for Re values of 10,000; with smaller multipliers at smaller Re. However this increase in friction is accompanied by an increase in the film heat transfer coefficients of 2 to 5 times (for a Re near 10,000) and a heat transfer increase of 7 to 15 times at a Re near 1,000. To achieve the same pressure drop as in tubular heat exchangers at the same process conditions the length of PHE channel (and the corresponding length of the plates) is made much shorter. The thermal and hydraulic performance of PHE channels is highly dependent on the geometry of the corrugations (especially the corrugation angle, β). As discussed by Arsenyeva et al. (2013), the geometry of the plates and corrugations can be optimised to satisfy specific process conditions. By combining plates with various corrugation geometries, PHE designs can be produced that satisfy a specific range of process conditions. Nowadays, PHE manufacturers are producing a large variety of plates with different corrugation sizes, heights and forms. This enables a variety of designs and the production of industrial PHEs with a heat transfer area that is much smaller (a reduction of 2 to 4 times) than traditional shell and tube heat exchangers.

One of the most important features of heat transfer designs using enhanced surfaces is the significant mitigation of fouling. As discussed by Crittenden et al. (2015) this is especially predominant for crystallisation and particulate fouling mechanisms. Fouling thermal resistance is shown to be reduced up to 10 times that of a conventional surface, furthermore the heat transfer surface remains clean for longer time periods (when threshold fouling conditions are reached with traditional systems).

A wide variety of industrial processes involve the transfer of heat energy and many of those processes employ old technology; this makes those processes ideal candidates for a redesign using enhanced surfaces that would produce improved process performance. The use of enhanced heat transfer surfaces will recover more energy and provide an opportunity to advance the design of many heat transfer products.

3. Conclusions

Nowadays a large number of passive methods for heat transfer intensification in tubes and channels are developed and investigated. These methods sufficiently reduce the required heat transfer area of the heat exchangers that are required to maintain the desired process conditions; alternatively they are able to increase the efficiency of heat transfer equipment and to improve heat recuperation, save energy and decrease emissions (CO^2 and other harmful emissions) to the environment that are generated during the energy production from fossil fuels.

The selection of particular method for heat transfer intensification depends on the process conditions where the heat transfer equipment is used. When retrofitting the existent shell and tube heat exchangers, enhancing tube inserts can be employed or changing the tubes for enhanced tubes. Economic considerations of a new enhanced shell and tube heat exchanger; tube replacement with enhanced tubes;

or the use of PHEs must also be considered in the evaluation of a heat exchanger. The grass root design of heat transfer equipment for new processes must consider all possible options for the use of heat exchangers with heat transfer intensification.

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