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Possibilities of Intensifying Heat Transfer in Heat Exchangers for High Temperature Applications

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A high temperature heat transfer application actually represents the case of a heat exchanger operated within a process with high temperature. In every industrial domain, a different value of temperature may be considered "high". We are active in the field of chemical, petrochemical, waste-to-energy, power and process energy recovery heat transfer applications. In these applications a tube-fin exchangers are successfully used for gas or liquid and/or aggressive fluids with temperatures up to 350 and/or 400 °C. They are also frequently used in combustion systems with air preheating applications. Tubular heat exchangers, especially those with U-tubes, helical and straight tubes are most frequently used for high-temperature applications with working temperatures above 650 °C.
Extended surfaces are used as an intensification approach to decrease the area requirements on flue gas side. Selection of an extended surface depends on type of fuel. In the case of combustion of fuels producing flue gas with fouling tendency, studded tubes are preferred. More efficient finned tubes may be used if fuel burnt produces relatively clean flue gas. Generally enhanced surfaces are used for gaseous media with low heat transfer coefficient. Fins substantially enhance the heat transfer area and consequently heat duty of the equipment.
Improving heat transfer performance is commonly referred to as heat transfer enhancement. Enhancement is usually represented by increasing the (film and overall) heat transfer coefficient by so called "passive" (surface extension) or "active" (increasing fluid turbulence) way.
This paper presents a possible selection of novel types of longitudinally finned tubes intensifying the heat transfer utilizing both passive and active principles. It means that fins not only increase heat transfer area but also make the fluid flowing around fin to change the flow direction, i.e., to increase the turbulence. This allows increasing the film heat transfer coefficient on fin-side.

1. Introduction

First it is necessary to solve the overall system in agreement with the process in question (e.g. Klemeš et al., 2010) and then to consider heat exchanger networks (HEN) and heat exchangers as pieces of equipment. A novel design approach for solving HEN retrofit based on heat transfer enhancement is shown in (Wang et al., 2011). The views and experience from industrial practice in terms of providing technical solutions for increasing the performance of heat exchangers through process enhancement technologies is presented in (Gough, 2012).
Heat exchangers perform satisfactorily only if they are correctly designed, installed, and operated. Selection of a suitable heat exchanger type, especially in case of high-temperature applications, is therefore of paramount importance.

1.1 Definition of "high temperature application"

High temperature application actually means that the equipment is operated within a process with high temperature streams. The problem, however, is how to define "high temperature". In every industrial domain, a different value may be considered "high", that is, a very different value will be denoted as such e.g. in cryogenics and in incineration. Even in respect to the human body, high temperature is understood

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in various ways. For example, the human body has normal temperature not above 37 °C and temperature around 38 °C is already a fever, while temperature above 40 °C is considered an extreme, so-called hyperpyrexia. Burns may already occur upon touching a surface hotter than 45 °C (depending on the actual temperature and time of the touch). In food industry, temperatures above 80 °C are usually considered high. In electronics, high temperature is typically above 85 °C (Joshi and Wei, 2005).
In any case, this paper is focused on the field of chemical, petrochemical, waste-to-energy, power, and process energy recovery heat transfer applications. In petrochemical industry, high temperature means values above 400 °C. A different situation arises considering combustion processes where high temperature flue gas is generated. There it is possible to classify as high temperature applications equipment with process stream temperatures above 650 °C (but then again, different sources give different values).

1.2 Suitable types of heat exchangers for high temperature applications

In general, it can be noted that for high temperature and highly fouled flue gas industrial applications heat exchangers with plain tubes or plate-type exchangers should be preferred wherever possible. These configurations allow easy cleaning of both outer and inner heat transfer surfaces. Tubular heat exchangers, especially those with U-tubes, helical, and straight tubes are most frequently used for high-temperature applications with working temperatures above 650 °C (Stehlík, 2009).
In case of applications with low risk of fouling, the common approach is to use a conventional plate type heat exchanger with modular arrangement. Basic information about this type of heat exchanger can be found e.g. in (Mayinger and Klas, 1992)), rules of design in, (Kuppan, 2000) and high temperature applications in; (Aquaro and Pieve, 2005). Typical temperature ranges for using compact plate type heat exchangers are obvious from Figure 1. However, these pieces of equipment have to be designed very carefully.
Authors of this article have an experience with such an application (in addition to other ones) where a conventional plate type heat exchanger type was originally used for high temperature purpose. The plates were manufactured from special fire-proof chrome-nickel steel. Unfortunately, this heat exchanger was not designed correctly in terms of thermal expansion and the operating conditions specified in documentation were not respected either. Combination of these two facts resulted in distortion of the plates and complete destruction of the exchanger (Stehlík, 2011).

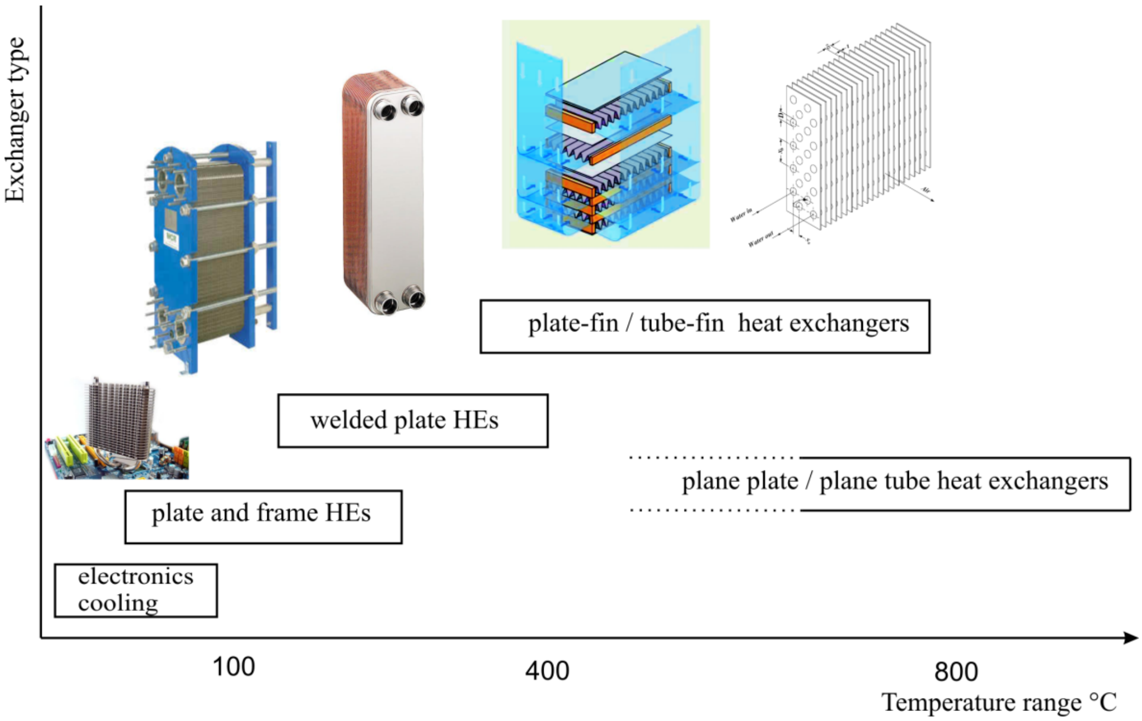


Figure 1: Types of compact heat exchangers and their typical temperature limits (Stehlík, 2011)

Finned tubes can also be used with success in case of low fouling applications. The actual temperature range in which finned tubes can be employed depends of the material they are made of. More on this topic

can be found in (Kuppan, 2000). According to Shah and Sekulić (2003), tube-fin exchangers are designed to cover the operating temperature range from low cryogenic temperatures to about 870 °C.
A typical example of application with finned tubes is a convection section of a fired heater. Convection section is located above the shield section and flue gas temperature there is between 500 °C and 700 °C. If there is no risk of fouling, usage of fins is possible. If there is any chance of fouling by flue gas, lower degree of heat transfer enhancement can be used, such as studded heat transfer surfaces (Jegla, 2006).
First part of furnace convection section is followed by the second part where flue gas temperature reaches 300 °C to 500 °C. Based on our extensive experience we can state that there is possible to fully utilize the potential of enhanced solutions (with respect to fouling properties of flue gas).
Finned tubes are also frequently used in combustion systems with air preheating equipment. These applications are probably the areas with the highest potential for application of enhanced solutions associated with increasing significance of heat recovery in this temperature range.
According to the above-mentioned information it can be noted that for high-temperature and highly fouled flue gas industrial applications heat exchangers with plain tubes or plate-type ones should be preferred. Such configurations allow easy cleaning of both outer and inner heat transfer surfaces.
For very high gas temperatures (above 500°C) and low risk of fouling one can safely use heat exchangers with enhanced heat transfer surfaces (with respects of enhanced surface material limit) and therefore intensify heat transfer. As a consequence, such equipment is then smaller.

2. Heat transfer intensification

Process heat transfer intensification is a design philosophy that aims at achieving reduced size of heat transfer equipment and the associated benefits (especially improving heat transfer performance). Thus, the product of intensification techniques is achieving any, or a combination, of the following (Energy Efficiency Office, 2000):

- reduction in size of the heat exchanger for a given duty;
- increase in capacity of an existing heat exchanger;
- reduction in approach temperature difference;
- reduction in pumping power.

Intensified heat transfer will increase efficiency, which will lead to energy conservation and reduced costs. However, some techniques may increase power consumption, either directly or due to increased flow resistance through the exchanger.
Intensification techniques can be divided into two classes:

- passive techniques, such as enhanced surfaces, requiring no direct application of external power;
- active techniques, such as rotation, consuming external power.

2.1 Passive techniques

Passive heat transfer intensification techniques include mainly (Energy Efficiency Office, 2000):

- enhanced surfaces;
- rough surfaces;
- displaced enhancement devices;
- swirl flow devices;
- coiled tubes.

A comprehensive description can be found e.g. in (Web and Kim, 2005). There are many recent approaches in this area as e.g. those using enhanced heat transfer tubes which results in increasing fluid turbulence, secondary flow development, disruption of the thermal boundary layer and increasing the heat transfer surface area (Kukulka et al., 2011) and later (Kukulka and Smith, 2012).
Let us focus on seeking for a new way of the passive technique consisting in enhanced surfaces.

2.2 New types of longitudinal fins

Considering flow along tubes, mainly longitudinal fins are used. Although these increase heat transfer area and thus cause an increase in heat transfer rate, the increase in turbulence is almost non-existent. This is why such fins are used only if there is no other viable option. In contrast, swirl flow devices increase primarily turbulence.
Ideally, one would want to obtain a geometry providing both larger heat transfer area and larger flow turbulence (such as in plate-type heat exchangers with compression-moulded plates). Newly developed types of longitudinally finned tubes that improve both the above-mentioned parameters are discussed further in the text.

3. Newly developed longitudinal finned tubes

Novel ways of longitudinal finning designs were developed by the authors just recently. These provide heat transfer intensification via enlargement of heat transfer area as well as increased turbulence.

3.1 Type 1

This design consists of fins manufactured by making cuts shaped as “upside-down T” and alternately bending the created flaps (see Figure 2). Of course, height of the fins is not fixed and can be chosen according to the actual operating conditions (viscosity of the fluid, its temperature, etc.), relevant rules of thumb and experience of the designer considering similar equipment and its behaviour, and last but not least requirements of the operator of the apparatus. In addition, geometry of the cuts can be fine-tuned as necessary.

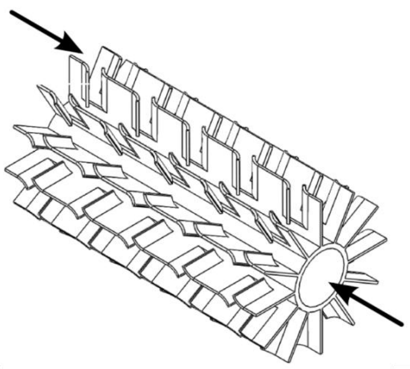
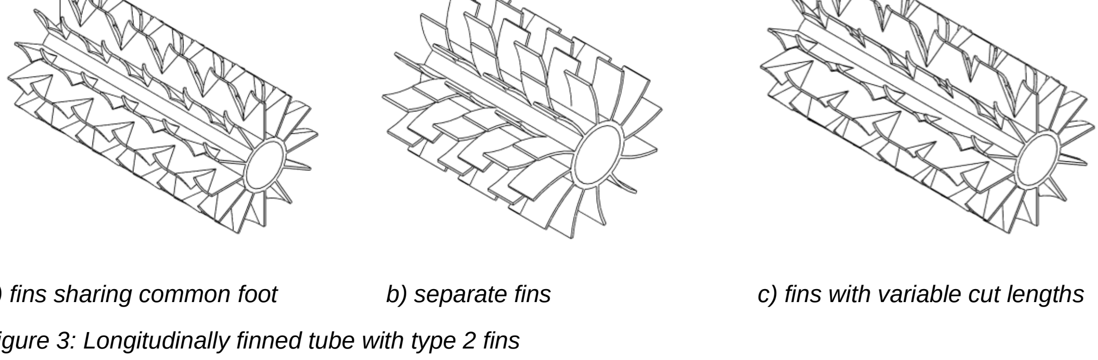


Figure 2: Longitudinally finned tube with type 1 fins created by making “upside-down T” cuts and bending the resulting flaps

3.2 Type 2

Here, cuts – either down to the feet of the fins or only partial ones – are made perpendicularly to the axis of the tube. The resulting flaps are again bent into alternate directions. In other words, we can either make fins that share a common foot (see Figure 3a), or separate fins (see Figure 3b). Compared to the type 1 fins, one can obtain flow with turbulence being either lower (Figure 3a) or higher (Figure 3b). Obviously, geometry providing higher turbulence provides higher heat transfer rate as well. Since this way we can only control heat transfer coefficient for the fin-side, geometry as in Figure 3b is recommended should the enhancement obtainable by type 1 fins be insufficient or should the type 1 fins be unsuitable. On the other hand, fin geometry such as in Figure 3a is recommended should heat transfer enhancement provided by type 1 fins be too large. The same applies if pressure drop caused by type 1 fins is unacceptable. Then fins shown in Figure 3a seem to be the right choice that will ensure both higher heat transfer rate and reasonable increase in pressure drop. Similarly as in case of type 1 fins, geometry can be optimized to provide the required enhancement of heat transfer coefficient by making the fins longer or shorter, wider or narrower, with longer or shorter cuts, etc. One can even combine different cut lengths in a single row of fins – see Figure 3c.



a) fins sharing common foot *b) separate fins* *c) fins with variable cut lengths*

Figure 3: Longitudinally finned tube with type 2 fins

3.3 Type 3
Type 3 fins are made by cutting semi-circles or semi-ellipses into the original fin sheets and bending the created flaps out in alternate directions (see Figure 4). While type 1 and type 2 fins can only be used if there is no (or negligible) risk of fouling, type 3 fins can be utilized even if little to moderate fouling is expected (due to the fluid turbulence flow along the shape of fins). What is more, heat transfer rate of an exchanger with this type of enhancement can be improved on demand by simply reversing the direction of flow along the tubes (as denoted by the dashed arrow in Figure 4). This is due to the fact that such a reversal leads to further increase in turbulence and thus also to increased heat transfer coefficient. On the other hand we have to consider increased pressure drop. Additionally, reversal of flow direction causes dislocation of pieces of the existing fouling layer, i.e., a noticeable cleaning effect.

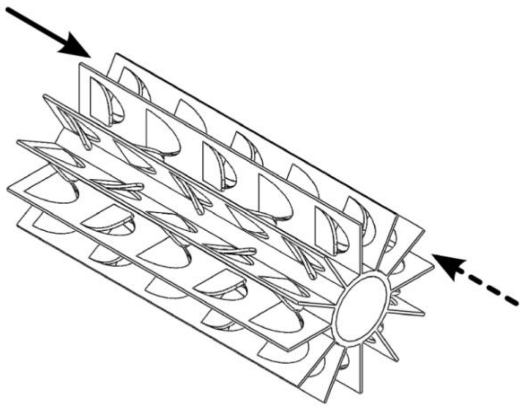


Figure 4: Longitudinally finned tube with type 3 fins

3.4 Type 4
This type of fins is a combination of type 1 and type 3 fins, or type 2 and type 3 fins. In other words, these fins make use of both perpendicular or "upside-down T" cuts and cut-out semi-circles or semi-ellipses. Again, flaps resulting from the cuts are bent in alternate directions. This type of fins combines the advantages of the previously mentioned types and can be tailored to the needs of individual pieces of heat transfer equipment.
In summary, the four above-mentioned new fin types provide both increased heat transfer area and higher turbulence which is the core benefit of these patented designs.

4. Potential applications

Research and development of such enhancement was initiated by potential industrial applications for power / heat and power plants where heat exchangers with the new fin types can substantially influence the size and cost of up-to-date thermal cycles and their applicability not only for conventional power systems applications like those for waste heat utilization but also for new and modern environmentally efficient plants such as integrated heat and power (CHP) plants, power plants based on biogas utilization and the like.
As a typical potential application of presented new fin types can be mentioned heat transfer equipment for efficient steam-air mixture preheating (typically up to 500 – 550 °C) by hot flue gas (with a typical temperature level 600 – 650 °C). Such a preheater is very frequently used not only in classical thermo dynamical cycles but also in CHP plants. Increased heat duty of such preheater in combination with low pressure drop can bring important investment and operating savings of such plants together with low plant built-up area requirements.

5. Conclusions

High temperature applications are commonly used in every branch of industry. The problem, however, is how to define "high-temperature applications." That is why this was discussed in the introduction of the paper along with types of heat exchangers used in these applications – particularly exchangers with enhanced heat transfer surfaces.

With new materials being created, there is a tendency to establish new ways of heat transfer intensification (especially via surface enhancements). This is why the new design of longitudinally finned tubes was constructed – it enhances heat transfer by both increased surface area and increased flow turbulence. The presented types of the new design are being developed at the authors' institute.

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