

# Heat Transfer Enhancement in Different Corrugations – A Review

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**ABSTRACT** - Heat transfer enhancement techniques can be divided into two categories passive and active. In passive heat transfer enhancement an object which does not use external energy, such as groove inside the tube, has the role of increasing the heat transfer rate. The forced convection heat transfer is used for the analyzing the heat transfer in heat exchangers. CFD is a best tool in the process of industries not only for the research and development of new processes but also for understanding and optimization of existing process. This paper mainly focused on the different heat transfer enhancement techniques used for improving the heat transfer rate in the different geometric configurations of the tubes.

**KEYWORDS:** Computational fluid dynamics and heat transfer enhancement techniques.

## I. INTRODUCTION

In conventional smooth tubes have low heat transfer rate and pressure loss. In order to improve the heat transfer rate with low pressure loss the use of extended surfaces or internally grooved surfaces are used because the corrugated tubes create extra turbulence in the fluid that flows through the tubes. The extra turbulence translates itself to an increase in the heat transfer of corrugated tubes. There are various methods used for heat transfer augmentation of increasing the heat transfer rate for heat exchanging from one medium to another.

### A. Heat Transfer Augmentation Methods

In general, heat transfer augmentation methods are classified into two 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, use of a magnetic field to disturb the seeded light particles in a flowing stream, mechanical aids, surface vibration, fluid vibration electrostatic fields, suction, injection and jet impingement requires an external activator or power supply to bring about the enhancement.

#### *Passive method*

This method generally uses surface or geometrical modifications to the flow channel by incorporating inserts or additional devices. For example, inserts extra component, swirl flow devices, treated surface, rough surfaces, extended surfaces, displaced enhancement devices, coiled tubes, surface tension devices and additives for fluids. Although there are hundreds of passive methods to enhance the heat transfer performance, the following nine are most popular used in different aspects:

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- Treated Surfaces*: They are heat transfer surfaces that have a fine-scale alteration to their finish or coating. The alteration could be continuous or discontinuous, where the roughness is much smaller than what affects single-phase heat transfer, and they are used primarily for boiling and condensing duties
- Rough surfaces*: They are generally surface modifications that promote turbulence in the flow field, primarily in single-phase flows, and do not increase the heat transfer surface area. Their geometric features range from random sand-grain roughness to discrete three-dimensional surface protuberances.
- Extended surfaces*: They provide effective heat transfer enlargement. The newer developments have led to modified fin surfaces that also tend to improve the heat transfer coefficients by disturbing the flow field in addition to increasing the surface area.
- Swirl flow devices*: They produce and superimpose swirl flow or secondary recirculation on the axial flow in a channel. These devices include helical strip or cored screw type tube inserts, twisted tapes. They can be used for single phase or two-phase flows heat exchanger.
- Coiled tubes*: These techniques are suitable for relatively more compact heat exchangers. Coiled tubes produce secondary flows and vortices which promote higher heat transfer coefficient in single phase flow as well as in most boiling regions.
- Displaced enhancement devices*: These are the insert techniques that are used primarily in confined force convection. These devices improve the energy transfer indirectly at the heat exchange surface by displacing the fluid from the heated or cooled surface of the duct/pipe with bulk fluid to the core flow.
- Additives for liquids*: These include the addition of solid particles, soluble trace additives and gas bubbles into single phase flows and trace additives which usually depress the surface tension of the liquid for boiling systems.
- Additives for gases*: These include liquid droplets or solid particles, which are introduced in single-phase gas flows either as dilute phase (gas–solid suspensions) or as dense phase (fluidized beds).
- Surface tension devices*: These consist of wicking or grooved surfaces, which directly improve the boiling and condensing surface. These devices are most used for heat exchanger occurring phase transformation

## B. Mechanisms of Augmentation of Heat Transfer

To the best knowledge of the authors, the mechanisms of heat transfer enhancement can be at least one of the following.

- (1) Use of a secondary heat transfer surface.
- (2) Disruption of the unenhanced fluid velocity.
- (3) Disruption of the laminar sub layer in the turbulent boundary layer.
- (4) Introducing secondary flows.
- (5) Promoting boundary-layer separation.
- (6) Promoting flow attachment/reattachment.
- (7) Enhancing effective thermal conductivity of the fluid under static conditions.
- (8) Enhancing effective thermal conductivity of the fluid under dynamic conditions.
- (9) Delaying the boundary layer development.
- (10) Thermal dispersion.
- (11) Redistribution of the flow.
- (12) Modification of radioactive property of the convective medium.
- (13) Increasing the difference between the surface and fluid temperatures.
- (14) Increasing fluid flow rate passively.
- (15) Increasing the thermal conductivity of the solid phase using special nanotechnology.

Methods using mechanisms no. (1) and no. (2) include increasing the surface area in contact with the fluid to be heated or cooled by using fins, intentionally promoting turbulence in the wall zone employing surface roughness and tall/short fins, and inducing secondary flows by creating swirl flow through the use of helical/spiral fin geometry and twisted tapes. This tends to increase the effective flow length of the fluid through the tube, which increases heat transfer but also the pressure drop. For internal helical fins however, the effect of swirl tends to decrease or vanish all together at higher helix angles since the fluid flow then simply passes axially over the fins [5]. On the other hand, for twisted tape inserts, the main contribution to the heat transfer augmentation is due to the effect of the induced swirl. Due to the form drag and increased turbulence caused by the disruption, the pressure drop with

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flow inside an enhanced tube always exceeds that obtained with a plain tube for the same length, flow rate, and diameter. Turbulent flow in a tube exhibits a low-velocity flow region immediately adjacent to the wall, known as the laminar sub layer, with velocity approaching zero at the wall. Most of the thermal resistance occurs in this low velocity region. Any roughness or enhancement technique that disturbs the laminar sub layer will enhance the heat transfer [6]. For example, in a smooth tube of 25.4mm inside diameter, at  $Re = 30,000$ , the laminar sub layer thickness is only 0.0762mm under fully developed flow conditions. The internal roughness of the tube surface is well-known to increase the turbulent heat transfer coefficient. Therefore, for the example at hand, an enhancement technique employing a roughness or fin element of height 0.07mm will disrupt the laminar sub layer and will thus enhance the heat transfer. Accordingly, mechanism no. (3) is a particularly important heat transfer mechanism for augmenting heat transfer. Li et al. [5] described the flow structure in helically finned tubes using flow visualization by means of high-speed photography employing the hydrogen bubble technique. They used four tubes with rounded ribs having helix angles between  $38^\circ$  and  $80^\circ$  and one or three fin starts, in their investigation. Photographs taken by them showed that in laminar flow, bubbles follow parabolic patterns whereas in the turbulent flow, these patterns break down because of random separation vortices. Also, for tubes with helical ridges, transition to turbulent flow was observed at lower Reynolds numbers compared to smooth tube values. Although swirl flow was observed for all tubes in the turbulent flow regime, the effect of the swirl was observed to decrease at higher helix angles. Li et al. [5] concluded that spiral flow and boundary-layer separation flow both occurred in helical ridging tubes, but with different intensities in tubes having different configurations. Arman and Rabas [7] discussed the turbulent flow structure as the flow passes over a two-dimensional transverse rib. They identified the various flow separation and reattachment/ redevelopment regions as: (a) a small recirculation region in front of the rib, (b) a recirculation region after the rib, (c) a boundary layer reattachment/redevelopment region on the downstream surface, and finally (d) flow up and over the subsequent rib. The authors noting that recirculation eddies are formed above these flow regions, identified two peaks that occur in the local heat transfer—one at the top of the rib and the other in the downstream recirculation zone just before the reattachment point. They also stated that heat transfer enhancement increases substantially with increasing

Prandtl number. Therefore, the mechanism no. (6) plays an important role in heat transfer enhancements heat transfer enhancements associated with fully/partially filling the fluidic volume by the porous medium take place by the following mechanisms [8, 9]. Ding et al. [10] showed that fluids containing 0.5wt.% of carbon nanotubes (CNT) can produce heat transfer enhancements over 250% at  $Re = 800$ , and the maximum enhancement occurs at an axial distance of approximately 110 times the tube diameter. These types of mixtures are named in the literature as “nanofluids” and it will discuss later on in this report. The increases in heat transfer due to presence of nanofluids are thought to be associated with the mechanism.

## II. HEAT TRANSFER ENHANCERS

From the concise summary about mechanisms of enhancing heat transfer described in last section, it can be concluded that these mechanisms cannot be achieved without the presence of the enhancing elements. These elements will be called as “heat transfer enhancers”.

### A. Heat Transfer Enhancement Using Extended Surfaces (Fins)

#### Fins

Fins are quite often found in industry, especially in heat exchanger industry as in finned tubes of double-pipe, shell-and-tube and compact heat exchangers [15–20]. As an example, fins are used in air cooled finned tube heat exchangers like car radiators and heat rejection devices. Also, they are used in refrigeration systems and in condensing central heating exchangers. Moreover, fins are also utilized in cooling of large heat flux electronic devices as well as in cooling of gas turbine blades [21]. Fins are also used in thermal storage heat exchanger systems including phase change materials [22–25]. According to design aspects, fins can have simple designs, such as rectangular, triangular, parabolic, annular, and pin rod fins. On the other hand, fin design can be complicated such as spiral fins [26, 27]. In addition, fins can have simple network as in finned tubes heat exchangers [20]. In contrast,

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they can be arranged in a complex network as can be seen in the works of [28–30]. Moreover, fins can be further classified based on the fact whether they interact thermally with a single fluid reservoir or with two different fluid reservoirs. Example of works based on the last classification is the works of Khaled [31, 32]. In addition, fins can be attached to the surface as in the works [15–25] or they may have roots in the heated/cooled walls [13]. Finally, fins can be solid [3, 4, 15–25] or they can be porous [33].

## *B. Laminar Single-Phase Heat Transfer in Finned Tubes.*

Laminar flow generally results in low heat-transfer coefficients and the fluid velocity and temperature vary across the entire flow channel width so that the thermal resistance is not just in the region near the wall as in turbulent flow. Hence, small-scale surface roughness is not effective in enhancing heat transfer in laminar flow; the enhancement techniques employ some method of swirling the flow or creating turbulence [6]. Laminar flow heat transfer and pressure drop in “microfin” tubes (discussed later) was experimentally measured by. Their data showed that the heat transfer and pressure drop in microfin tubes were just slightly higher than in plain tubes and they recommended that microfin tubes not be used for laminar flow conditions. This outcome has also been confirmed in the investigations of Shome and Jensen who concluded that “microfinned tube and tubes with fewer numbers of tall fins are ineffective in laminar flows with moderate free convection, variable viscosity, and entrance effects as they result in little or no heat transfer enhancement at the expense of fairly large pressure drop penalty”.

## *C. Turbulent Single-Phase Heat Transfer in Finned Tubes.*

Turbulent flow and heat transfer in finned tubes has been widely studied in the past and the literature available on the experimental investigations of turbulent flow and heat transfer in finned tubes is quite extensive. One of the earliest experimental work on the heat transfer and pressure drop characteristics of single-phase flows in internally finned tubes when Hilding and Coogan presented their data for ten different internal fin geometries for a 0.55 in. (14mm) inner diameter copper tube with 0.01 in. (0.254mm) straight brass fins using air as the test fluid. Hilding and Coogan observed that the heat transfer is enhanced by around 100–200% over that of the smooth tube and the enhancement is accompanied by a similar increase in the pressure drop. The Reynolds number in this study ranged from 15,000 to 50,000.

Kalinin and Yarkho used different fluids in the range  $1500 \leq Re \leq 400,000$  and  $7 \leq Pr \leq 50$  to investigate the effect of Reynolds and Prandtl numbers on the effectiveness of heat transfer enhancement in smoothly outlined internally grooved tubes. The ranges of the transverse groove heights tested were  $0.983 \leq d/D \leq 0.875$ , (where  $d$  is the fin tip diameter and  $D$  is the inner diameter) with maximum groove spacing equal to the pipe nominal diameter. They reported that the critical Reynolds number at which transition to turbulent flow occurs decreased from 2400 for a smooth tube to 1580 at  $e/D = 0.875$  and fin spacing equal to half the pipe diameter for a grooved tube, with a maximum increase in the heat transfer coefficient of up to 2.2 times the minimum measured value. The authors also observed that the behavior of the Nusselt number for the tested range of Prandtl numbers is independent of the Prandtl number.

In their two papers, Vasilchenko and Barbaritskaya published their results for the heat transfer and pressure drop of turbulent oil flow in straight finned tubes with  $4 \leq N \leq 8$  and  $0.13 \leq e/D \leq 0.3$ , for an operating condition range of  $103 \leq Re \leq 104$  and  $70 \leq Pr \leq 140$ . Their results showed that the heat transfer is enhanced by 30% to 70% over that of smooth tubes for the finned tubes tested. Correlations for predicting the friction factors and the Nusselt numbers were also presented. In the work of Bergles et al. heat transfer and pressure drop data for straight and spiral finned tubes of fin heights from 0.77 to 3.3mm with water as the working fluid was investigated. The Reynolds number based on the hydraulic diameter ranged from around 1,500 to 50,000. They found an earlier transition from laminar to turbulent flow and their friction factor data indicated that the smooth tube friction factor correlations could also be used for the tested finned tubes in the turbulent region. The heat transfer coefficients were found to be up to twice that of comparable smooth tubes. From their heat transfer data, they concluded that the hydraulic diameter approach is effective for correlation only in the case of straight fins of moderate heights.

Since their introduction more than 20 years ago, “microfin” tubes have received a lot of attention playing a very significant role in modern, high-efficiency heat transfer systems. Microfin enhancements are of special interest

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because the amount of extra material required for micro fin tubing is much less than that required for other types of internally finned tubes. Of the many enhancement techniques which have been proposed, passively enhanced tubes are relatively easy to manufacture, cost-effective for many applications, and can be used for retrofitting existing units, whereas active methods, such as vibrating tubes, are costly and complex. Moreover, these tubes ensure a large heat transfer enhancement with a relatively small increase in the pressure drop penalty. Micro fin tubes are typically made of copper and have an outside diameter between 4 and 15 mm. The principal geometric parameters that characterize these tubes are: the external diameter, fin height (from 0.075 mm to 0.4 mm), helix angle (from 10° to 35°), and the number of fin starts (from 50° to 60°). These dimensions are in contrast to other types of internal finning that seldom exceed 30 fins per inch and fin heights that range from several factors higher than the micro fin tube height. Currently, tubes with axial and helical fins, in rectangular, triangular, trapezoidal, crosshatched, and herringbone patterns are available. Important dimensionless geometric variables of internally micro finned tubes include the dimensionless fin height ( $\varepsilon/D$ , fin height/internal diameter) and the dimensionless fin pitch ( $p/\varepsilon$ , fin spacing/fin height). A micro fin tube typically has  $0.02 \leq \varepsilon/D \leq 0.04$  and  $1.5 \leq p/D \leq 2.5$ . As micro finned tubes are typically used in evaporators and condensers, thus most of the extensive existing research literature on micro finned tube performance characteristics is devoted to two-phase refrigerant flows. Schlager et al. and Khanpara et al. are typical examples of such investigations, showing a 50% to 100% increase in boiling and condensation heat transfer coefficients with only a 20% to 50% increase in pressure drop. However, single-phase performance of microfinned tubes is also an important consideration in the design of refrigeration condensers as a substantial proportion of the heat transfer area of these condensers is taken up in the desuperheating and later sub cooling of the refrigerant. Consequently, accurate correlations for predicting the single-phase heat transfer and pressure drop inside microfinned tubes are necessary in order to predict the performance of these condensers and to optimize the design of the system.

### III. CONCLUSION

In this paper, the following heat transfer enhancers are described and reviewed: (a) extended surfaces including fins and microfins, (b) porous media, (c) large particles suspensions, (d) nanofluids, (e) phase-change devices, (f) flexible seals, (g) flexible complex seals, (h) vortex generators, (i) protrusions, and (j) ultra high thermal conductivity composite materials. Different research works about each one have been reviewed and many methods that assist their enhancement effects have been extracted from the literature. Among of these methods presented in the literature are using joint-fins, fin roots, fin net works, bi convections, permeable fins, porous fins, helical microfins, and using complicated designs of twisted tapes. It was concluded that more attention should be made towards single phase heat transfer augmented with microfins in order to alleviate the disagreements between the works of the different authors. Also, it was found that additional attention should be made towards uncovering the main mechanisms of heat transfer enhancements due to the presence of nanofluids. Moreover, we concluded that perhaps the successful modeling of flow and heat transfer inside porous media, which is a well recognized passive enhancement method, could help in well discovering the mechanism of heat transfer enhancements due to nanofluids. This is due to some similarities between both media. In addition, it is concluded that noticeable attentions from researchers are required towards further modeling flow and heat transfer inside convective media supported by flexible/flexible-complex seals in order to compute their levels of heat transfer enhancements. Eventually, many recent works related to passive augmentations of heat transfer using vortex generators, protrusions, and ultra high thermal conductivity composite material have been reviewed.

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