METALFORMS
HEAT TRANSFER

TWISTED TUBE HEAT EXCHANGERS:
TECHNOLOGY AND APPLICATION

Heat exchangers are usually classified by the compactness factor in m_2/m_3 and it is generally accepted that values greater than 700 m_2/m_3 characterize compact equipment. Although shell-and-tube exchangers can have high a compactness factor, compact heat exchangers are often referred to as non-tubular devices. This paper describes an advanced shell-and-tube heat exchanger using twisted tubes. Recent advances in the range of design and operational reliability have made twisted tube heat exchangers attractive in various industries, including offshore application. Taking into account size and convenience considerations, these exchangers can be cost effective in a wider range of applications than the niches currently being used in the process industry, in the Nusselt, Reynolds, Prandtl equation form. Total friction factor through a twisted-tube bundle was found to be the sum of axial friction loss component and a drag contribution from the swirl flow.

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INTRODUCTION

Most heat exchangers, including twisted tubes, have yet not been exploited commercially to their fullest potential. This may be a surprising feature of the current industrial practice, particularly in the context of viscous liquid applications, where substantial heat transfer enhancement can still be achieved. In spite of the abundance of technical information, the critical need is still the availability, or lack of generalized thermal-hydraulic design guidelines. The majority of correlations are for turbulent flows; laminar and particularly transition flows have received little attention in spite of the fact that relatively higher heat transfer augmentation is possible in low Reynolds number flows. This is because historically, early heat transfer enhancement devices were limited mostly to gas flow applications, such as fire-tube boilers.

The need for more efficient, smaller size exchangers in all varieties has resulted in the development of many heat transfer surfaces that claim to be more efficient than conventional tubes. This makes a selection of surface configuration for a particular application by no means a simple task. Just as most issues are seldom black or white, so are most good solutions seldom unequivocal. Every single truth has a domain of its validity; outside the domain the truth does not hold. Dealing with the heat transfer and heat exchanger design follows these general principles. There is no solution that makes one technology absolutely superior, but there are technologies that for particular applications are better than others. The objective of this paper is to address some of these issues.

TWISTED TUBE EXCHANGERS

Heat transfer enhancement is one of the fastest growing areas of heat transfer technology. In fact many techniques are available for improvement of various modes of heat transfer. Second generation enhancement technology is already common in the process industry. Brown Fintube's recent research and development program is an effort to advance a third generation of heat transfer enhancement technology, twisted tube exchangers.

A twisted tube is a passive heat transfer enchantment device, generally classified in a swirl-flow device category. Swirl-flow devices consist of a variety of geometrical flow arrangements that produce forced vortex fluid motion in confined flows. The enhancement in all cases occurs primarily due to fluid agitation and mixing induced by swirl flow.

EXPERIENTIAL TESTING

An attractive feature of the twisted tube, Fig.1, is that swirl is not, as in other techniques, produced by a device attached to the tube. As such, they do not require an extra attention during assembly, maintenance, inspection, or cleaning.

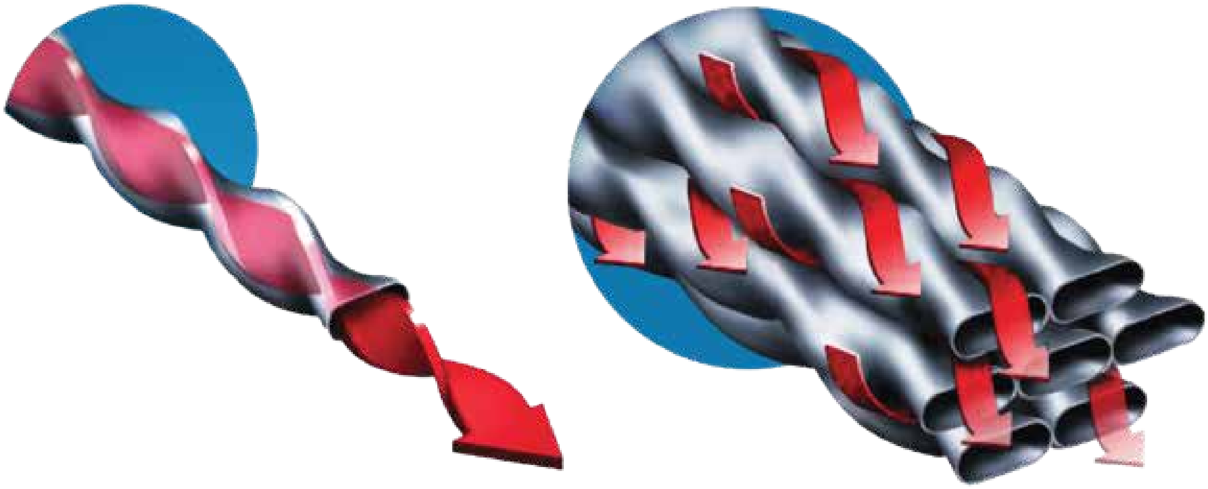

Figure 1. Tube-side and Shell-side Swirl Flow enhancement

These devices consist of helically twisted, double radius oval tubes, welded by their round ends to tubesheets. The tubes contact one another at their wider sides, six times over the length of one twist pitch, which makes the unit practically vibration free. The purely longitudinal shell-side flow in twisted tube bundles is rarely mentioned in the theory of heat exchangers design, despite its ability to provide considerable surface density, low-pressure drop, and high heat transfer coefficient. The bundle enhances heat transfer, tube-side and shell-side. The tube-side fluid becomes swirled, and is affected by wall turbulence and by the different fluid layer velocities. In the course of the shell-side flow over tubes, circulation and mixing is generated. A secondary circulation generated by the centrifugal force of swirling also affects the in-bundle flow. Inside and outside helically shaped tubes double to triple the overall heat transfer rate with about doubled hydraulic resistance. A simple use of such tubes instead plane, rounded tubes, is equivalent to a 30% reduction of the heat exchanger size while keeping a similar heat exchanger duty.

Geometry of the device is simple: tube twisted into a constant pitch helix. In the general configuration, the geometrical characteristics are defined by the 360 degree twist pitch, "s", tube profile $a \cdot b$, nominal diameter ratio to one of the sides, or bore to nominal diameter ratio. The severity of the twist is referred to by the dimensionless twist to diameter ratio $y = s/d_o$.

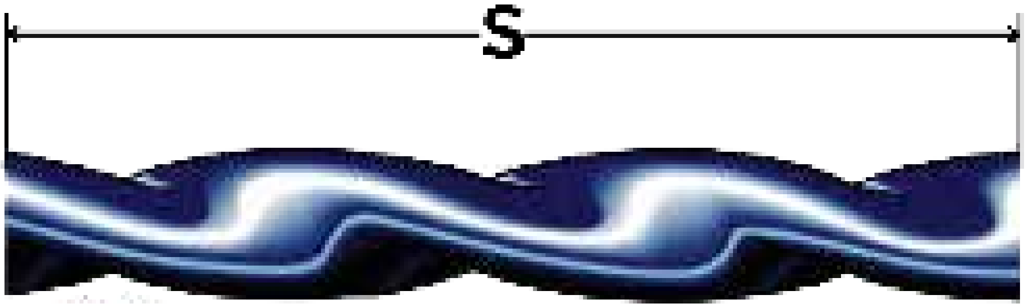

Figure 2. Twisted Tube Geometry

MATERIALS

Tubes can be made in a variety of materials: carbon steel, stainless steel, monel, brass, nickel etc.

MECHANICAL CHARACTERISTICS

Tubes are firmly supported while allowing a well distributed longitudinal flow along the tubes. While stresses and other mechanical considerations are similar to conventional baffled heat exchangers, the twisted tube bundles provide absolute resistance to vibration. Repair is the same or similar as for conventional heat exchangers.

MAINTENANCE

Tubes can be cleaned both tubeside and shell-side. However, because of the increased turbulence and well-distributed flow without stagnant zones, as is usually the case in baffled heat exchangers, twisted tube heat exchangers do not foul as easily. Also, these units are well suited for chemical cleaning.

COST

Twisted tube heat exchangers may seem costly, but when higher heat transfer area, lower total weight, and particularly operating costs are taken into account, they can be actually competitive and cost effective.

SWIRLFLOW

In helical channels, there is a secondary flow, as there is in straight channels flow in an irregular cross section due to anisotropy of turbulent stresses. Fluid particles near the tube axis have a larger velocity and are acted on by a larger centrifugal force than are slower particles near the wall. The resultant secondary flow is directed outward in the center of the tube and inward near the wall. This effect is stronger in laminar than in turbulent flow. Increased turbulence in twisted tube bundles improves heat transfer through reduction of the boundary layer thickness and through better mixing in the bulk. Since local velocity field and flow distribution are good, the heat transfer is more uniform, the heat transfer coefficient is generally the highest possible in tubular heat exchangers. Moreover, cross flow is always penalized compared to pure counter-current flow by correcting Δt_m. Pure longitudinal flow in twisted tube exchangers allows better use of the available temperature difference. To suggest how the high heat transfer coefficients in twisted tube exchangers are achieved, the helical channels can be looked upon as series of consecutive short sections between which the buildup of a steady velocity profile is interrupted by the constant direction change of the flow. Good transverse mixing is achieved by these interruptions, and the numerous disturbances keep the flow turbulent even at relatively low Reynolds numbers. Because build up to a fully developed profile is continuously disturbed by the pattern of twisted tubes, no influence from the entrance is recognized.

There are several equally important mechanisms influencing heat transfer in an individual twisted tube and in a bundle. In general, induced swirl in each individual tube will enhance turbulence mixing process and enhance or suppress other mechanisms.

If the cold fluid is on the shell side, as a result of centrifugal force, the radial pressure gradient will force heavier, colder fluid outwards, with a consequent rise of hot fluid toward the center of the pipe. This has a negative effect on the local heat transfer coefficient. The opposite will happen for hot fluid on the shell side. However, the flow distribution through the bundle is another factor influencing overall heat transfer. Data show that cooling shell-side fluid (with favorable density gradient) results in a less favorable flow distribution, lowering somewhat the overall heat transfer coefficient.

FLOW REGIMES

It is commonly thought the low Reynolds number flow regimes are typical of compact heat exchangers such as plate exchangers, and that high Reynolds numbers usually occur in shell-and-tube exchangers. For lower Reynolds numbers, typical enhancement methods seek to reduce the critical Reynolds number that separates laminar from transitional flow. In swirl flow this is accomplished by a deliberately developed secondary flow, and by stimulating the growth of boundary layer instabilities. The superimposed swirl flow will produce a heat transfer increase, but it will always introduce a pressure drop penalty, too. For the transition from the laminar to turbulent regime, the heat transfer enhancement is higher than the pressure drop increase. Enhancement for higher Reynolds numbers grows progressively more difficult because turbulent eddies become more and more vigorous with increasing Reynolds numbers, implying high turbulent diffusivity and high heat transfer coefficient. Thus, swirl flow induced enhancement in turbulent regime becomes less effective.

TESTING

The current Brown Fintube motivation is to identify the phenomenological behavior, understand the involved mechanisms, and develop design correlations that have general applicability.

Studies of the heat transfer and pressure drop of twisted-tube type exchangers were conducted, and the effects of changing various construction parameters were investigated. Experimental single-phase heat transfer and pressure loss data were obtained using a test rig with three different, commercial-size test exchangers. Seven different bundle configurations were tested, each design examining specific geometric parameters of the twisted-tube exchangers. Single-phase studies established a baseline reference for the convective in-tube boiling and shell-side shear controlled condensation tests which followed. The relative heat transfer improvements in laminar and transition flows are found to be substantially greater than those obtained in turbulent flows. Developed predictive equations have very good general applicability and cut through a wide spectrum of operating services, including different fluids, flow regimes, and heating and cooling duties.

As in the case with other swirl devices, characteristics of the two-phase flow in twisted tube are relatively different from those in smooth tube. Also it is reasonable to expect that twisted tubes will be beneficial in almost all phase change process applications.

In plain tube condensing applications, gravity and shear control flows normally represent completely different mechanisms, have different trends with respect to Reynolds number, and normally give widely different results. Tests have been conducted at NEL, Glasgow, (Fig.2), to develop correlations for twisted tubes shell-side condensation, and to establish a criterion needed to determine whether to use shear or gravity type equations. The data show the heat transfer coefficient is improved considerably. The main reason for the enhancement in condensing were identified as the liquid layer thinning effect due to the presence of the centrifugal force and the disturbance caused by the secondary flow.

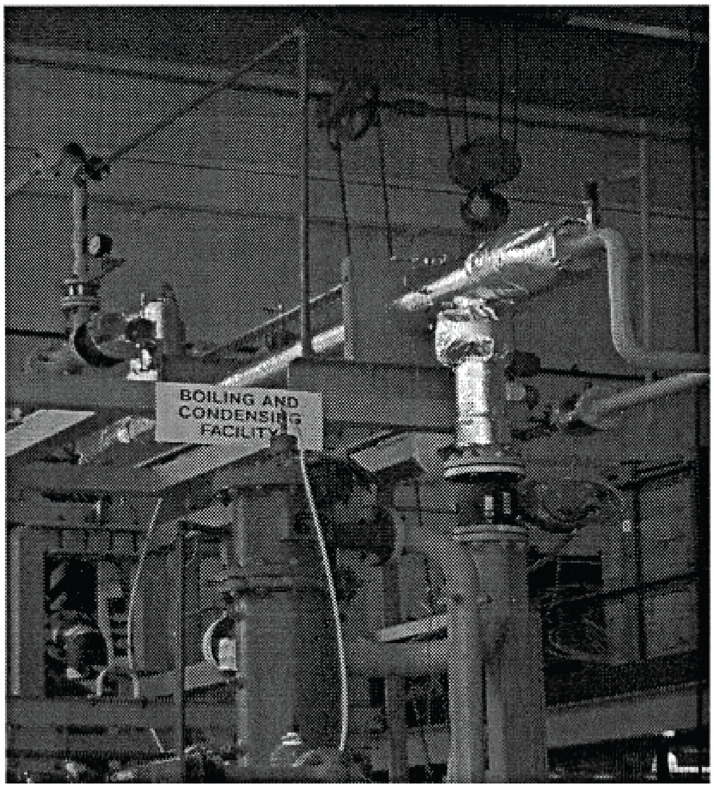

Figure 2. NEL Condensing Test Rig

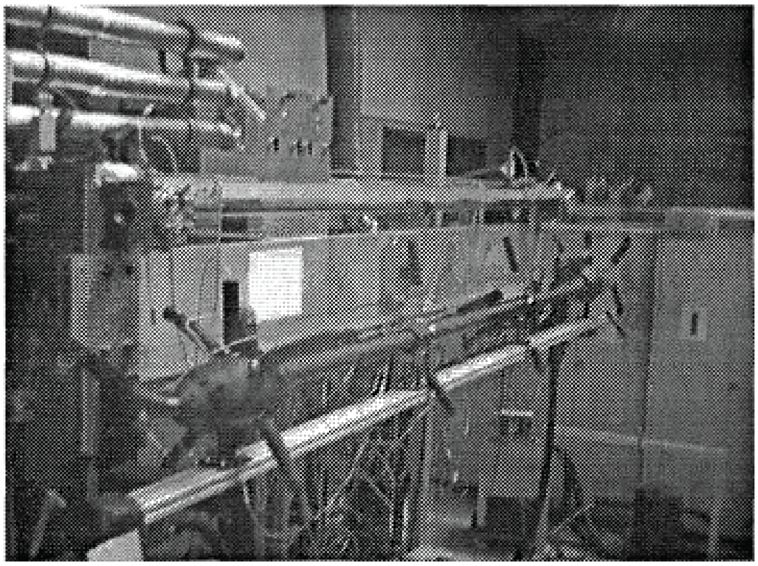

Figure 3. EPFL Boiling Test Rig

For the in-tube boiling, data of local heat transfer coefficients and pressure drops over the range of mass fluxes, vapor mass fractions, and heat fluxes in tubes with different twist pitches and profiles were collected at Swiss Federal Institute of Technology (EPFL), Losanne, Fig.3. This study focused on the flow and boiling mechanisms in horizontal twisted tubes.

The data proved the twisted tube helical channels are effective in augmenting heat transfer, and even more importantly, preventing and postponing the dry-out boiling crises. With obtained local heat transfer coefficients and pressure drop data BFT is developing general predictive methods for twisted tube heat exchangers in boiling applications.

All studies overwhelmingly confirmed the merits of twisted-tube exchangers and it is now possible to provide accurate guidance on performance rating and sizing of such units. Also, it was demonstrated that these exchangers could be tuned to a particular application by optimizing design of the tube profile.

COMPARISONS

When discussing the heat transfer under the different conditions, in most cases it is difficult to make direct (and correct) comparison using the inlet and outlet temperatures and pressure drop. Generally, the compared systems are so differently conceived that the calculated heat transfer coefficients serve only as a guideline. Only in the rare case when the two compared units are identical in the type of construction, can the heat transfer coefficient be used as a measure for direct comparison. In comparing twisted tube to conventional, baffled heat exchangers, it should be noted that compactness of twisted tube bundles itself leads to higher performance. A more compact surface has smaller flow passages, and the heat transfer coefficient always varies as a negative power of the hydraulic diameter of the passage. Thus, a twisted tube bundle compact surface, compared to a plain tube bundle, tends by its very nature to have higher heat transfer coefficient. This leads to higher overall performance, despite the adverse effect smaller hydraulic diameter has on the frictional pressure drop.

The thermal effectiveness in heat exchangers largely depends on the shell-side flow distribution governed by the heat exchanger geometry. In shell-and tube units, a number of segmental baffles help to support the tubes and to balance cross flow velocity for increased shell-side heat transfer within the allowable pressure drop. Excessive pressure drops and the leaks and bypasses are often unavoidable. A twisted tube exchanger provides almost ideal longitudinal shell side flow distribution offering better conversion of available pressure drop to heat transfer.

For evaluating heat exchangers under the same operating conditions, the heat transfer coefficient is normally assumed as a basic measure of efficiency and then other factors as pressure drop, cost, and maintenance, are considered. From the relationship between conformity to physical laws, operating conditions and geometry, correlations are developed in which heat transfer coefficient is dependent on certain characteristic parameters. However, comparing these correlations from different sources shows that often a false or a deceiving picture of the efficiency of heat exchanges could be established.

Some commonly used parameters for heat transfer effectiveness are:

Number of heat transfer units,

$$\Theta = \frac{t_i - t_o}{\Delta t_m}$$

and specific pressure drop defined as,

$$J = \frac{\Delta p}{\Theta}$$

Twisted tube heat exchangers are generally economically justified when the heat transfer rate is relatively high, i.e. for exchangers where,

$$\frac{t_i - t_o}{\Delta t} > 0.2 - 0.3$$

or for fluids with the viscosity greater than 1cSt

CONCLUSION

It is ultimately apparent that the development of rationally optimized heat exchanger design with new superior surface characteristics could be achieved only if the basic phenomena are well known and understood. In spite of considerable activity, the field of enhanced heat transfer is not "routine". In fact it is anything but ordinary. Experimentation is difficult, modeling of the phenomena is not very simple, and the most sophisticated analytical and numerical techniques are required to get results that are reasonably useful to practicing engineers.

However, recent tests and advances in the range of design and operational reliability have made twisted tube heat exchangers attractive in various industries, including offshore application. Their high performances already have been confirmed throughout the petro-chemical industry. Twisted tube exchangers are generally more expensive than a conventional shell-and-tube exchangers, but their payback time is not necessarily longer. Taking into account size and convenience considerations, these exchangers can be cost effective in a wider range of applications than the niches currently recognized in the process industry.

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