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Heat transfer evaluation of an enhanced heat transfer tube bundle

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ABSTRACT

Demands to increase performance of modern heat exchange systems are constantly being made. Typical requirements include the removal of larger amounts of energy or the development of process units that occupy a smaller unit footprint. Vipertex™ 1EHT enhanced surfaces have been designed and produced through material surface modifications in order to create flow optimized heat transfer tubes which increase heat transfer with only a modest increase in the friction factor. Considerations in the development of the enhanced, three dimensional 1EHT enhanced heat transfer surfaces include: maximization of heat transfer; minimization of operating costs; and/or a minimization of the rate of surface fouling. This study details the performance of a horizontal oriented 1EHT enhanced surface tube bundle and compares heat transfer results to a horizontal bundle of smooth tubes for single phase and two phase conditions. Results for the 1EHT bundle show an increase in the overall heat transfer coefficient up to 200% when compared to the heat transfer performance of a smooth tube bundle using typical fluids (n-Pentane, p-Xylene and water); for midpoint shellside Reynolds number values in the range of 2010–20,400; with effective mean temperature difference (EMTD) values between 8.6 °C and 65.7 °C. More nucleation sites are produced on the 1EHT tube surface than on an equivalent length of unenhanced commercial tube. Results from this bundle study indicate that the 1EHT enhanced tube surface is well suited for applications where nucleate boiling is significant. Enhanced heat transfer tube bundles using the 1EHT tubes are capable of producing efficiency increases making 1EHT tubes an important alternative to be considered in the design of high efficiency processes. Vipertex 1EHT tube bundles recover more energy and provide an opportunity to advance the design of many heat transfer products.

1. Introduction

Boiling heat transfer is the mode of heat transfer used in various heat exchange components (evaporators, chillers, refrigeration systems, power generation components, desalination systems, petrochemical/process applications, etc.). Many industrial processes that involve the transfer of heat energy employ old designs; making those processes ideal candidates for a redesign utilizing enhanced surfaces that improve system performance. Heat transfer from a tube bundle is considerably different than the heat transfer from a single tube since the vapor bubbles generated on lower tubes rise and cause heat transfer enhancement in the upper tubes. Some applications have been designed on the basis of heat transfer results obtained from a single tube and that could lead to inefficient designs.

Gough [1] discusses the increased demand on the performance of heat exchangers and the need to enhance their performance. Enhanced heat transfer techniques are still relatively new and the results are not always predictable. Additionally, experimentation is complex and modeling can be complicated, with meaningful results sometimes difficult to obtain. Enhancements in boiling heat transfer processes are vital in order to make typical industrial applications more energy efficient. Enhanced surfaces with cavities on the surface promote nucleate boiling and reduce the required wall superheat necessary for nucleate boiling to occur. Heat transfer enhancements for boiling applications in tubular products are available; however there are limitations on the range/ enhancement structure of the enhanced tubes used in that regime; additionally many of the currently available enhanced tubes are expensive to produce and operate.

Nucleate boiling is a type of boiling that takes place when the material surface temperature exceeds the saturated fluid temperature and the heat flux is below the critical heat flux. When boiling is initiated, bubbles form at nucleation sites and flow

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from the surface; this results in the fluid mixing near the surface, causing an increase to heat transfer. An enhanced 1EHT tube provides more nucleation points than an equivalent smooth tube resulting in an increase to heat transfer and allows more advanced designs to be considered. Processes that are expected to benefit the most include designs in which a fluid is required to boil on the outside of a tube bundle with low heat flux; process units that utilize flooded-type or full-liquid type evaporators would be greatly enhanced. These types of designs have been widely used in many industrial heat exchange applications and include: desalinization, liquid gas evaporators, solar-powered absorption chillers, etc.

"Bundle effect" has been shown to significantly influence the heat transfer in the smooth upper tubes within the bundle. Heat transfer due to nucleate boiling increases more in the upper tubes than the lower tubes at low heat fluxes. These enhancements disappear for high heat flux, fully developed nucleate boiling regions; in these regions the data for all tubes merge onto the pool boiling curve of a single tube. In order to satisfy design requirements, some designs need to utilize enhanced tubes in order to increase boiling heat transfer at low heat fluxes. In desalinization devices and other heat exchangers making use of low quality heat energy, both wall temperatures and heat fluxes are generally quite low and cannot produce boiling on smooth heated tubes with common tube spacing. Little heat transfer data exists for some typical fluids (i.e. hydrocarbons, etc.) and that leads to excessive safety margins that typically produce oversized (in terms of process area) heat exchangers.

Advantages of enhanced designs include an increase in the heat transfer coefficient; smaller unit footprint; more economic operation costs; and a prolonged product life. There are a few heat exchanger design scenarios to consider, the most common design method utilizes a one-for-one replacement of smooth tubes with enhanced tubes of equal length; producing heat transfer increases for a constant fluid flow rate, this is typically characterized by an increase in the pumping power requirement of the enhanced tube heat exchanger. Another scenario to consider is a constant pumping power design; in this case the required tube length could be reduced. Finally for the case of constant heat transfer in the same unit footprint; the use of enhanced tubes will reduce the pumping power requirements. The current heat transfer study evaluated the latest generation of enhanced 1EHT bundles for single phase and two phase conditions.

Ulbrich and Mewes [2] utilized visual observations and a statistical analysis to propose a classification of flows that include bubbly, intermittent and dispersed flows. Noghrehkar et al. [3] point out that using only visual observation as a flow regime indicator could lead to false conclusions. They use the probability density function (PDF) of fluctuations in the local void fraction to identify regime and flow patterns near the shell wall. However, those patterns vary from the patterns present in the bundle core. Burnside et al. [4] used particle image velocimetry (PIV) autocorrelation techniques to describe the time dependent flow beneath and to the side of a smooth tube bundle in boiling pentane. Iwaki et al. [5] used PIV to characterize the velocity fields, vortex structure and turbulent intensity in two different smooth tube bundle configurations. Aprin et al. [6] ran a series of tube bundle experiments that measured the void fraction of a variety of test fluids (n-pentane, iso-butane and propane). Ribatski and Thome [7] showed that the void fraction is one of the most important parameters used in the analysis of tube bundle flows. Their study points out important discrepancies that take place when using visual observations that are not backed up by measurements.

Cornwell et al. [8] demonstrate that the heat transfer characteristics in a tube bundle are significantly different than those obtained from a single tube. They discuss how important an understanding of enhanced heat transfer begins with an understanding of the fluid properties involved and the interaction of the fluid with the tube bundle. Browne and Bansal [9] have presented an overview of the heat transfer characteristics of flooded tube bundle evaporators with boiling on the outside surface of the tubes. They discuss the influence of tube position and study various configurations using smooth tube bundles. Aprin et al. [10] present a paper that deals with heat transfer analysis for boiling flow in a staggered tube bundle. Through optical fiber methods they determine the heat transfer coefficient of various regions in the bundle. They also include a detailed literature survey of several existing bundle studies. Daróczy et al. [11] present results from a CFD (computational fluid dynamics) study of a tube bundle in a cross-flow heat exchanger that examined the tube arrangement and found the optimal geometry necessary to maximize the rate of heat exchange while minimizing pressure loss. Van Rooyen [12] evaluated enhanced boiling tubes from Wolverine Tube and Wieland-Werke AG using R134a and R236. High-speed videos were obtained that characterize the boiling process. Measurements of the heat transfer and pressure drop from a single tube and a bundle configuration were also performed.

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 [1] points out that the recent natural disasters in Japan have prompted the Japanese government to take a more active role in its serious drive to reduce energy use. Recently, additional countries (i.e. United States, Korea, Denmark, etc.) have been promoting energy efficiency; making the development of enhanced heat transfer tubes and other enhanced heat transfer technologies even more important.

Several Vipertex enhanced heat transfer tube designs have been optimized for specific heat exchange requirements. These tubes have been designed and produced through material surface modifications, creating flow optimized heat transfer tubes. Kukulka et al. [13] evaluated enhanced tubes under fouling conditions and presented detailed transient efficiency results of the 1EHT tubes. In another study, Kukulka and Smith [14] evaluated the surface geometry of enhanced tubes. These works have formed the groundwork for this present tube bundle study.

Previous smooth tube bundle studies have demonstrated that heat transfer in a tube bundle differs from the heat transfer in a single tube. In a previous single tube enhanced study [14] that evaluated single phase heat transfer performance, the performance of the specific 1EHT enhanced tube is compared to a smooth tube; this is necessary so that a multiplier can be arrived at in order to characterize the performance of the tube. This same method is utilized in the current study since the tube used in the tube bundle has surface characteristics specifically designed to achieve performance objectives. These characterizations would be difficult to model for various enhanced tubes and to be inclusive of all enhanced tubes. Specifically in this study, tube bundles created from Vipertex 1EHT enhanced heat transfer tubes were used to evaluate single phase and boiling conditions in a heat exchanger bundle. These measurements provide overall HTC multipliers that were previously unavailable for these enhanced tube bundles. Single phase heating is a convection heat transfer phenomenon that has the dominate contribution made by the bulk or gross motion of fluid particles. Typically in this heat transfer mode the convective heat transfer coefficient increases as the Reynolds number (*Re*) increases. However, as Kukulka and Smith [14] point out for some conditions, this is not always the relationship. There

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