CHEMICAL ENGINEERING TRANSACTIONS

VOL. 35, 2013

A publication of
AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Varbanov, Jiří Klemeš, Panos Seferlis, Athanasios I. Papadopoulos, Spyros Voutetakis

ISBN 978-88-95608-26-6; **ISSN** 1974-9791

DOI: 10.3303/CET1335075

Evaluation of a 1EHT Enhanced Heat Transfer Tube Bundle for Processes Involving Boiling

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Demands to increase performance of modern heat exchange systems are constantly being made; requiring the removal of larger rates of energy, using process units that occupy a smaller unit footprint. Heat transfer enhancement plays an important role in improving energy efficiency and developing high performance thermal systems. Heat transfer processes that involve boiling are typically efficient modes of heat transfer; however the desire to increase efficiencies of those processes have prompted the development of enhanced heat transfer surfaces for boiling processes. A wide variety of industrial processes involve the transfer of heat energy during phase change and many of those processes employ old technology. These processes would be ideal candidates for a redesign that could achieve improved process performance.
Utilization of enhanced heat transfer tubes is an effective method used in the development of high performance thermal systems. Vipertex™ enhanced surfaces, have been designed and produced through material surface modifications, which result in flow optimized heat transfer tubes that increase heat transfer. Considerations in the development of the optimized, three dimensional, enhanced heat transfer Vipertube design include the maximization of heat transfer; minimization of operating costs; and minimization of the rate of surface fouling. This study details the 1EHT bundle boiling results over a wide range of conditions. Results for the 1EHT bundle show combined overall bundle increases of shellside and tubeside heat transfer up to 97 % when compared to the heat transfer enhancement of a smooth tube bundle using typical fluids (n-Pentane, p-Xylene and water); for midpoint shellside Reynolds number values in the range of 2,800 to 20,400; with effective mean temperature difference (EMTD) values between 15.4 ^{O}F (-9.2 ^{O}C) and 118.3 ^{O}F (47.9 ^{O}C). Enhanced heat transfer tube bundles that are capable of producing efficiency increases in excess of 90 % are important options to be considered in the design of high efficiency processes. These enhanced tube bundles recover more energy and provide an opportunity to advance the design of many heat transfer products.

1. Introduction

Boiling heat transfer is used in a variety of industrial processes utilizing various heat exchangers, evaporators, chillers, refrigeration systems, power generation components, desalination systems and petrochemical applications. 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. Gough (2012) 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 difficult and modeling can be complicated; with meaningful results sometimes difficult to obtain. Enhancements in boiling heat transfer processes are vital, and make typical industrial applications more energy efficient. Rough or 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

Please cite this article as: Kukulka D., Smith R., 2013, Evaluation of a 1eht enhanced heat transfer tube bundle for processes involving boiling, Chemical Engineering Transactions, 35, 451-456 DOI:10.3303/CET1335075

in tubular products are available; however the limited options of enhanced tubes used in that flow regime are sometimes limited in range and/or enhancement; and in addition, expensive to operate and produce.

Nucleate boiling is a type of boiling that takes place when the material surface temperature is hotter than the saturated fluid temperature and the heat flux is below the critical heat flux. When boiling is initiated for a range of temperature differences, bubbles form at nucleation sites and flow from the surface, producing fluid mixing near the surface, accompanied by an increase in heat transfer. It is shown that the Vipertex 1EHT enhanced tube used in such applications would provide more nucleation points than an equivalent smooth commercial tube, increasing heat transfer and advancing the designs of those products. Processes expected to benefit the most include those using flooded-type or full-liquid type evaporators, in which a fluid boils on the outside of a tube bundle; these have been widely used for desalinization, solar-powered absorption chillers, and other types of industrial heat exchange applications.

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 optimization scenarios to be considered including: a one-for-one replacement of smooth tubes with enhanced tubes of equal length producing heat transfer increases for a constant fluid flow rate; typically increasing the pumping power requirement of the enhanced tube heat exchanger. Another scenario to consider is constant pumping power designs; 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 study evaluated the latest generation of enhanced 1EHT boiling tubes for a variety of conditions.

Visual observation and statistical methods were used by Ulbrich and Mewes (1994) who proposed a classification of flows that include bubbly, intermittent and dispersed flows showing liquid and vapor superficial velocities. Noghrehkar et al. (1999) pointed out that the use of only visual observations as a flow regime indicator could lead to false conclusions. They used the probability density function (PDF) of local void fraction fluctuations to indicate the flow regime and they identified flow patterns near the shell wall; those patterns varied from the patterns in the bundle core. Burnside et al. (2005) and Iwaki et al. (2004) used particle image velocimetry to characterize the velocity fields inside the bundle. They tested a very short bundle butted up against a plexiglass end plate in order to view the flows. Aprin et al. (2007) ran a series of void fraction measurement experiments in a tube bundle with a variety of test fluids (n-pentane, iso-butane and propane). Ribatski and Thome (2007) show that void fraction are one of the most important parameters inside tube bundles. Their analysis unveils important discrepancies in some methods using visual observations that are not backed up by more objective measurements of the flow regime. It is difficult to accurately model the heat transfer (evaporating fluid, layout of the bundle, etc) and fluid flow on the outer tube surfaces of a bundle of tubes for processes characterized by two phase flows. Furthermore, little heat transfer data exists for some fluids typically utilized (i.e. hydrocarbons and other process fluids). Due to these reasons, excessive safety margins are often utilized in thermal design and they typically oversized the heat exchanger in terms of process area.

Cornwell et al. (1980) shows that the heat transfer characteristics in a tube bundle are significantly different from those obtained from a single tube. The strong interactions between two-phase flow and tubes, combined with the reduction of the cross-section area and the disturbance due to the vapor production on adjacent and upstream tubes strongly modify the heat transfer mechanisms. Additionally, an understanding of enhanced heat transfer begins with an understanding of the fluid properties involved and their interaction with the heating surface and tube bundle. Browne and Bansal (1999) have presented an overview of the heat transfer characteristics of the flooded tube bundle evaporators and boiling on the outside tubes and tube bundles. They discuss the influence of tube position and configuration. Upper tubes within the bundle can significantly increase nucleate boiling heat transfer more than the lower tubes at low heat fluxes; this is known as the bundle effect. In the high heat flux regions of fully developed nucleate boiling, these influences disappear and the data for all tubes merge onto a pool boiling curve of the single tube. However, the designs of some systems require enhanced tubes to be used in order to increase boiling heat transfer at low heat fluxes. In desalinization devices and some heat exchangers making use of low quality heat energy, both wall temperatures and heat fluxes are generally quite low and cannot cause boiling on smooth heated tubes under common large tube spacing conditions. Therefore in order to advance those designs, enhanced surfaces must be used.

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 recent events 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. USA, 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.
Vipertex optimized several enhanced heat transfer tube designs which increase heat transfer on both the inside and outside surfaces. These tubes have been designed and produced through material surface modifications, creating flow optimized heat transfer tubes. Kukulka et al. (2011) evaluated enhanced tubes under fouling conditions and detailed transient results of the 1EHT tubes are presented. In another study, Kukulka and Smith (2012) evaluated the surface geometry of enhanced tubes and that study formed the groundwork for the tubes utilized in the present study. None of the conditions and/or geometries from the previous enhanced studies was the same as the present study; therefore no direct comparison could be made to previous enhanced works.

2. Experimental Details

Figure 1 provides views of the enhancements on the inner and outer surfaces of the 0.625 inch (15.875 mm) outer diameter Vipertex 1EHT enhanced stainless steel tube that was evaluated in this study. Boiling heat transfer characteristics of the enhanced Vipertex 1EHT heat transfer tubes were evaluated in water and then verified with in an experimental study at the Heat Transfer Research, Inc. (HTRI) Research and Technology Center. Additional 1EHT bundle evaluations took place in the HTRI study using shell side fluids of n-Pentane, water and p-Xylene with steam utilized inside the tube. Tube OD was 0.625 in (15.875 mm) with a 0.7813 in (19.85 mm) pitch and 30 deg tube bundle layout angle. One row of dummy tubes (same outer surface on the dummy row as in the middle rows), producing the continuous pattern necessary to simulate the flow pattern, in the center of the boiler. Both the smooth and 1EHT bundles were studied in cross flow in the same shell (11.75 in (298 mm) Shell ID).
Experiments were carried out with a staggered tube bundle with three fluids under a wide variety of operating conditions. These conditions are representative of typical industrial processes. Heat transfer coefficients deduced from the results are compared to smooth tube bundle correlations (Xace 7.0) from the HTRI database developed previously by HTRI from experimental work performed using the same apparatus.

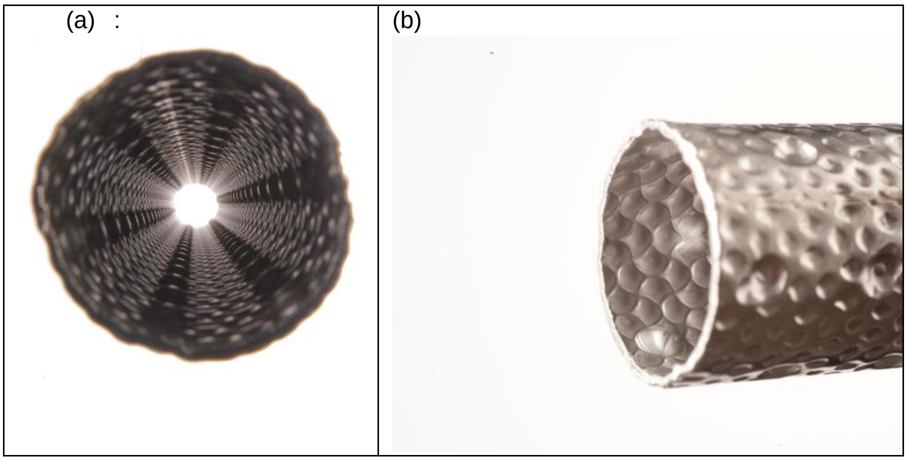


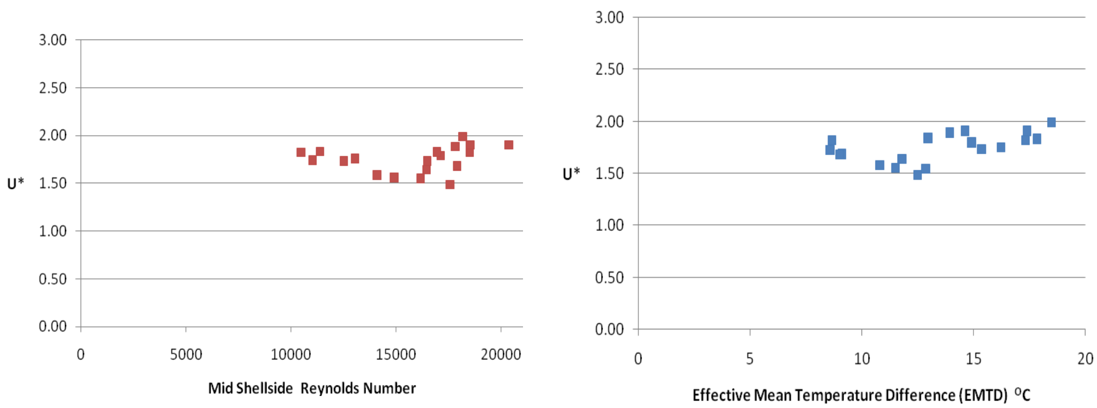
Figure 1: (a) Cross Sectional View showing details of the inner surface of Vipertex 1EHT (Type 304 L stainless steel) Enhanced Tube (b) Details of the Outer Surface of the Vipertex 1EHT (Type 304 L stainless steel) Enhanced Tube

3. Results

The overall heat transfer coefficient (tubeside heat transfer resistance, metal resistance and shellside heat transfer resistance) is measured for a variety of fluids with a wide range of flow and thermal conditions. Average duty is calculated based upon the average of: (i) steam condensate flow rate and the change in steam enthalpy; and (ii) test fluid flowrate, test fluid condensate rate and change in test fluid enthalpy. A comparison of overall heat transfer is necessary since the 1EHT tube is enhanced on both sides, making it difficult to differentiate the heat transfer on the tube or shell side. Additional future testing will allow a tubeside/ shellside differentiation.

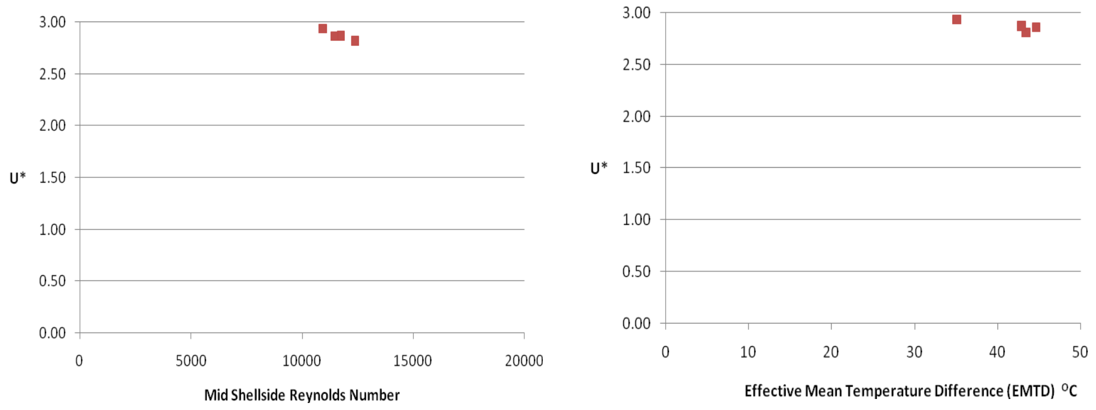
Figures 2a (n-Pentane), 3a (water) and 4a (p-Xylene) compares the variation of the mid-shellside Reynolds Number with the overall heat transfer ratio, U* (overall heat transfer coefficient for the Vipertex 1EHT enhanced tube bundle, U_{1EHT}, divided by the overall heat transfer coefficient in the smooth tube bundle, U_{Smooth}). Overall 1EHT bundle enhancement, is shown in Figure 2a for n-pentane under pressure; showing a maximum enhancement of 99 % and a minimum of 49% when compared to a smooth tube bundle. Local maximum enhancements appears for approximate Reynolds Numbers of 10,000 and 20,000, with the minimum enhancement (50 %) occurring for Reynolds Numbers near 15,000. Overall bundle enhancement, shown for water in Figure 3a, is almost 200 % and appears to be constant with no trend apparent over the limited Reynolds Number range evaluated. Overall 1EHT bundle enhancement is shown for p-Xylene (for pressures close to ambient pressure) in Figure 4a; and average enhancements of approximately 24 % are seen.

Figures 2b (n-Pentane), 3b (water) and 4b (p-Xylene) compare the variation of overall heat transfer ratio, U* (overall heat transfer coefficient for the Vipertex 1EHT enhanced tube bundle ,U1EHT, divided by the overall heat transfer coefficient in the smooth tube bundle, U_{Smooth}) with the Effective Mean Temperature Difference (EMTD) of the heat exchanger. Overall 1EHT bundle enhancement is shown in Figure 2b for n-pentane under pressure; showing a maximum performance, when compared to a smooth tube bundle at EMTD values greater than 13 ^{O}C. Overall bundle enhancement, shown for water in Figure 3b, is almost 200 % for the limited range evaluated. Overall 1EHT bundle enhancement is shown for p-Xylene (for pressures close to ambient pressure) in Figure 4b; and average enhancements of approximately 24 % are seen.



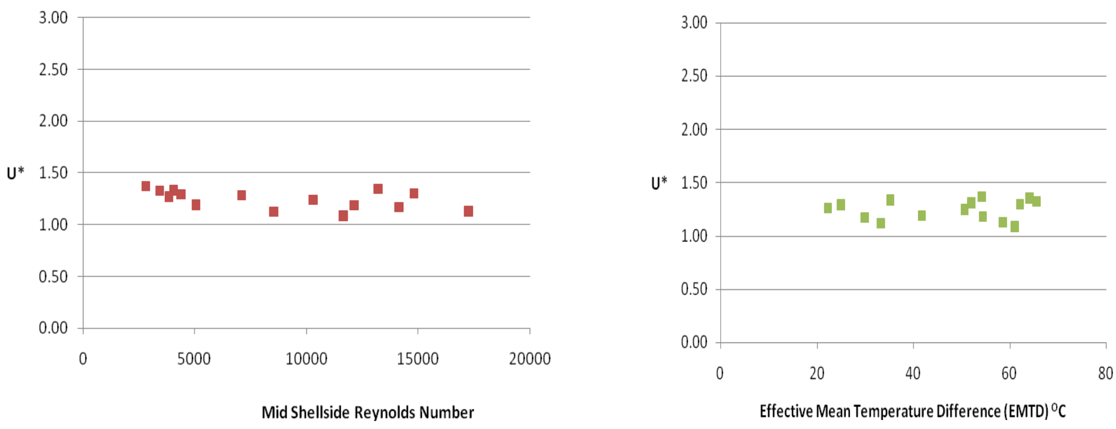
(a) (b)

Figure 2 Variation of the Overall Enhancement Ratio, U, (ratio of the overall heat transfer coefficient for the Vipertex 1EHT, Type 304 L stainless steel Enhanced Tube Bundle, U_{1EHT} ,to the overall heat transfer coefficient in the smooth tube bundle, U_{Smooth}), for n-Pentane used as the shellside fluid and its variation with (a) Mid-Shellside Reynolds Number (Re) (b) Effective Mean Temperature Difference (EMTD), °C*



(a) (b)

Figure 3: Variation of the Overall Enhancement Ratio, U, (ratio of the overall heat transfer coefficient for the Vipertex 1EHT, Type 304 L stainless steel Enhanced Tube Bundle, U_{1EHT} ,to the overall heat transfer coefficient in the smooth tube bundle, U_{Smooth}), for Water used as the shellside fluid and its variation with (a) Mid-Shellside Reynolds Number (Re) (b) Effective Mean Temperature Difference (EMTD), °C*



(a) (b)

Figure 4 Variation of the Overall Enhancement Ratio, U, (ratio of the overall heat transfer coefficient for the Vipertex 1EHT, Type 304 L stainless steel Enhanced Tube Bundle, U_{1EHT} ,to the overall heat transfer coefficient in the smooth tube bundle, U_{Smooth}), for p-Xylene used as the shellside fluid and its variation with (a) Mid-Shellside Reynolds Number (Re) (b) Effective Mean Temperature Difference (EMTD), °C*

4. Summary

The purpose of this study was to characterize the bundle boiling of a Vipertex 1EHT enhanced tube bundle using n-Pentane under pressure, in cross flow boiling on the outside of the tubes. Additional testing was performed on p-Xylene, at close to ambient pressure, in single phase heating on the outside of the tubes. Evaluation was carried out with tubes that had an OD that was 0.625 in (15.875 mm) with a 0.7813 in (19.85 mm) pitch and a 30 deg tube bundle layout angle, producing a continuous pattern that simulates the flow pattern in the center of the boiler. Both the smooth and 1EHT bundles were studied in cross flow, using the same size shell (11.75 in (298 mm) Shell ID). Experiments were carried out with a staggered tube bundle, with n-Pentane, water and p-Xylene under a wide variety of operating conditions. These conditions are representative of typical industrial processes.

A number of conclusions can be drawn from the results of this study:

- Results for the 1EHT bundle show combined overall bundle increases of shellside and tubeside heat transfer up to 97% when compared to the heat transfer enhancement of a smooth tube bundle for midpoint shellside Reynolds number values in the range of 2800 to 20400; with effective mean temperature difference (EMTD) values between 15.4 °F (-9.2 ° C) and 118.3 °F (47.9 °C).
- Overall bundle performance enhancement (1EHT) for n-pentane (under pressure) shows a maximum enhancement of 99 % and a minimum of 49% when compared to a smooth tube bundle. Local maximum enhancement appears for approximate Reynolds Numbers of , and 20,000, with the minimum enhancement (50 %) occurring for Reynolds Numbers near 15,000. Overall 1EHT bundle enhancement for water is almost 200 % and appears to be constant with no trend apparent over the limited Reynolds Number range evaluated. Overall 1EHT bundle enhancement for p-Xylene (at pressures close to ambient pressure) produce average enhancements of approximately 24 % .
- Bundle enhancement (1EHT) for n-pentane (under pressure) shows a maximum bundle performance enhancement of 99 % and a minimum of 49 % when compared to a smooth tube bundle. The 1EHT bundle shows a local maximum enhancement at EMTD values greater than 13 °C.

All this leads to an important and exciting advancement in process design. The patented Vipertex surface enhances heat transfer, conserves energy and minimizes cost. Additional studies at lower Reynolds numbers will take place since the level of enhancement at those rates is unclear. Additional bundle testing over a larger range of flows, temperatures and fluids may provide additional insight to the problem. Further studies of new Vipertex surfaces are currently under way.

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