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Enhanced Heat Transfer Surface Development for Exterior Tube Surfaces

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Enhanced heat transfer surfaces are produced by modifying the design of conventional process surfaces. Tubes and process surfaces that are enhanced are necessary in order to increase heat transfer, minimize operating costs and conserve energy. In a comparison of the first generation Vipertex enhanced heat transfer tubes with smooth surface tubes a performance increase in excess of sixty percent was found in the first generation Vipertex enhanced tubes. The current study was undertaken to further enhance heat transfer on the outer surface of these enhanced heat transfer tubes. Through the use of computational fluid dynamic (CFD) methods, a flow optimization study of the surface characters that are used to build the enhanced surface was performed. This study evaluates the effect of the character pattern and character geometry on the fluid flow and heat transfer of the process surface. As a result, a new process surface design was produced and then evaluated experimentally. Heat transfer efficiency was experimentally determined for low flows to be 125 % and for high flows (annulus Reynolds numbers, Re_A ~248,000) the increase was in excess of 250 % for the best performing Vipertex 1EHT enhanced tubes. Modest increases of the friction factor accompany these increases in heat transfer. Other tube versions provided smaller increases in heat transfer with a very small increase in the friction factor.
Heat transfer enhancement is important in the development of high performance thermal systems. Many industrial processes involve the transfer of heat energy and most employ old technology. If improved process performance is desired, redesign should be considered using enhanced surfaces. Enhanced heat transfer performance is the result of a combination of structured surface variations that are a result from this detailed surface study. Enhanced performance characteristics include: increased fluid turbulence, secondary fluid flow pattern enhancement, disruption of the thermal boundary layer and increased process surface area. These enhancement factors lead to an increase in the heat transfer coefficient; the ability to produce units with a smaller unit footprint; systems that are more economic to operate; and units with a prolonged life. This development provides a very important and exciting advancement in the design of processes that utilize heat transfer tubes and process surfaces.

1. Introduction

Agra et al. (2011) numerically investigated the heat transfer and pressure drop characteristics of smooth, corrugated and helically finned tubes using CFD analysis. Analysis was carried out for Reynolds Numbers ranging from 12,000 to 57,000. Water was used as a fluid and a constant temperature boundary condition was applied to the tube wall. Effects of the helix angle and ridge height on: the temperature difference between the fluid and the tube wall; magnitude of the pressure drop; and the convective heat transfer coefficient were investigated as a function of temperature, mass flux and Reynolds Number. Kumar et al. (2012) presents a summary of several CFD investigations detailing the effect of roughness geometries on the heat transfer and friction factor for heating ducts used in solar applications. Kukulka and Smith (2012) detail the development process and results for tubeside performance of an enhanced heat transfer tube. The Vipertex 1EHT enhanced tube showed outstanding thermal performance characteristics in the traditional laminar flow regime ($Re \leq 2200$) for inside fluid cooling

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conditions. A local Nusselt number maximum was observed at Reynolds numbers near ~750 for the Vipertex 1EHT tube. Heat transfer near Re = 750 is more than five times greater than the heat transfer of a smooth tube at the same conditions. Kukulka et. al (2011) presents performance of enhanced heat transfer tubes under fouling conditions. Reduction in the rate of fouling is the result of secondary flow patterns that form as a result of the patented Vipertex surface design. These secondary flows circulate near the tube surface and clean it; slowing down the buildup of materials. Vipertex EHT series tubes enhance heat transfer (even under fouling conditions), minimize operating costs and recover more energy than smooth tubes under the same conditions.

A modified form of Dittus-Boelter's (1930) classic correlation was used in the present study to compare the heat transfer coefficient, as a function of the annulus Reynolds number, on the outside of the 1EHT tube to that of a smooth tube. No other comparison can be made since the peak performance range considered in this study did not fall into the range considered in Agra et al. (2011) or Kumar et al. (2012).

In general the objective of this study is to optimize the surface pattern on an enhanced heat transfer surface in order to maximize heat transfer while minimizing pumping power and the rate of fouling for a certain range of flows. Enhancement characters used in the first generation Vipertex tubes were evaluated and modified. For the conditions considered, the new enhanced surface was then compared to an unenhanced surface using CFD analysis. Several patterns were modeled and the desired objectives evaluated (heat transfer, fouling, pumping power, low flow rates, turbulent flow, single phase, two phase, etc). Enhancement characters were then combined into patterns, and then multiple patterns combined to produce a design. These patterns were visualized and patterns refined to achieve the final results. This design was then used to produce the second generation Vipertex 1EHT enhanced surface. Heat transfer tubes were then produced and these tubes were experimentally evaluated.

2. Model

Models of the enhanced tube and smooth tube were created in order to study the enhancement effects of the proposed surfaces. In order to simplify the model, several assumptions have been adopted in this study including: 1) Negligible gravity and buoyancy effects; 2) Thermophysical fluid properties are constant; 3) Local thermodynamic equilibrium is satisfied; 4) Ambient temperature, T_∞ , is constant; 5) Flow is uniform with a constant velocity, U_∞ ; 6) Tube surface, for the smooth surface, has no-slip velocity boundary conditions.

Conservation equations with the appropriate boundary conditions are solved numerically using CFD2000, a commercial CFD code [Adaptive Research (2013)]. An initial study of the various enhancement characters was performed in order to determine the enhancement to be considered. In order to minimize the effect of the far-field boundary conditions, the outer boundary of the computational domain must be placed sufficiently far away from the tube. A rectangular domain was chosen to simulate the unbounded flow past the tube section in order to insure that the outer boundaries do not have any noticeable effect on the CFD simulation flow parameters. The model utilized a rectangular mesh, and the area around the cylinder wall was carefully meshed using a boundary layer technique that allowed the grid to be refined and minimized. This is necessary in order to observe the flow near the tube surface. Figure 1 shows a representation of the mesh for a sample enhancement character. Uniform incoming fluid velocity was set for the entry computation region and included the following sample conditions: inlet velocity, U_∞, of 1 ft /sec (0.3048 m / s); fluid inlet temperature, T_∞, of 70 ^{O}F (21.1 ^{O}C); and outer boundaries that are set as adiabatic. A standard wall function processing method is adopted near the wall.

Generally, the accuracy of a numerical solution increases as the number of cells increase. However, the use of a larger number of cells is restricted by the sophistication of the computer hardware and the computing time. Several meshes, with increasing refinement, were tested to ensure that the solution was independent of the mesh. The results of that evaluation showed that the variation of the pressure coefficient, p, for different grid schemes, is very small with a minimum relative difference; verification of mesh independence for a circular tube was obtained. A grid scheme was chosen for use by minimizing computation time and maximizing the accuracy of solution. Verification of mesh independence in the analysis of the enhanced tubes and verification of the method of the CFD simulation was undertaken in this study. Figure 2 shows a typical arrangement used in the centerline analysis of an enhancement character,.

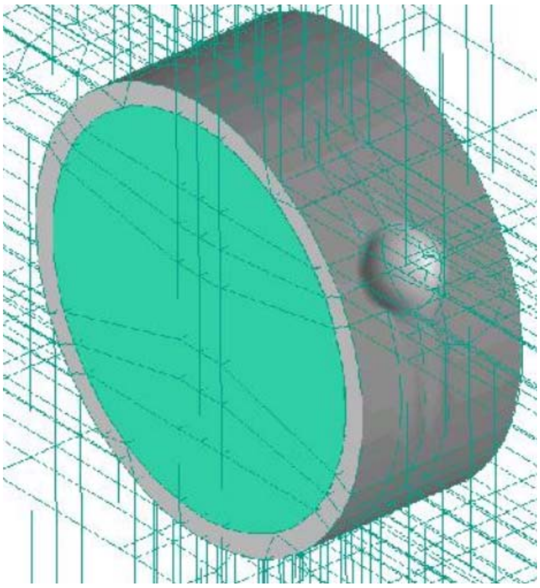


Figure 1: Typical mesh used for the CFD analysis of a surface enhancement

3. Results

The present analysis considers a 0.75 inch (1.905 cm) OD smooth tube and variations of the Vipertex 1EHT enhanced heat transfer tube that had a circular-shaped cross section and a 0.037 inch (0.094 cm) wall. Various enhancements were considered, with the final primary enhancements presented being: a dimple shape with a diameter of 0.2 inch (0.508 cm) and a smaller dimple with a diameter of 0.138 inch (0.351 cm). Other shapes were considered, but due to manufacturing considerations, the circular shapes were pursued. An enhancement character of a dimple on the inside produces a cavity on the outside surface.

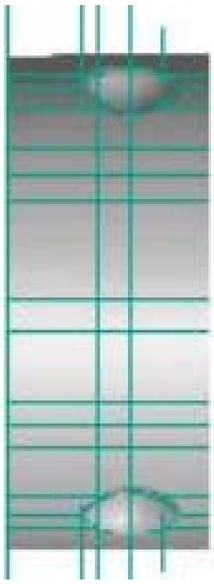


Figure 2: Mesh and center location used for the centerline CFD analysis on an enhancement character.

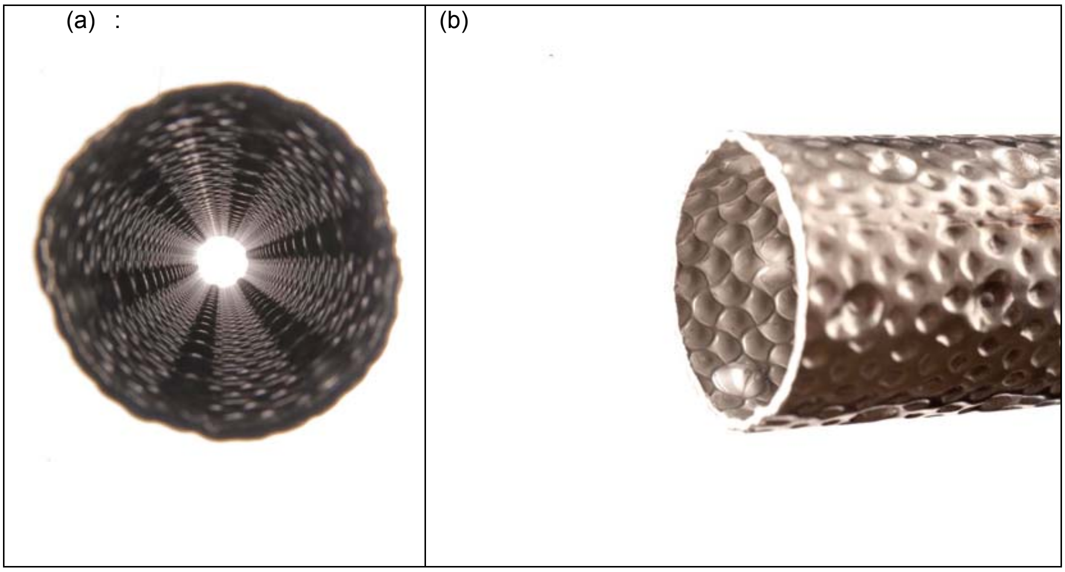


Figure 3 Details of the Vipertex 1EHT (Type 304 L stainless steel) Enhanced Tube (a) Cross sectional inner view (b) Outer surface.

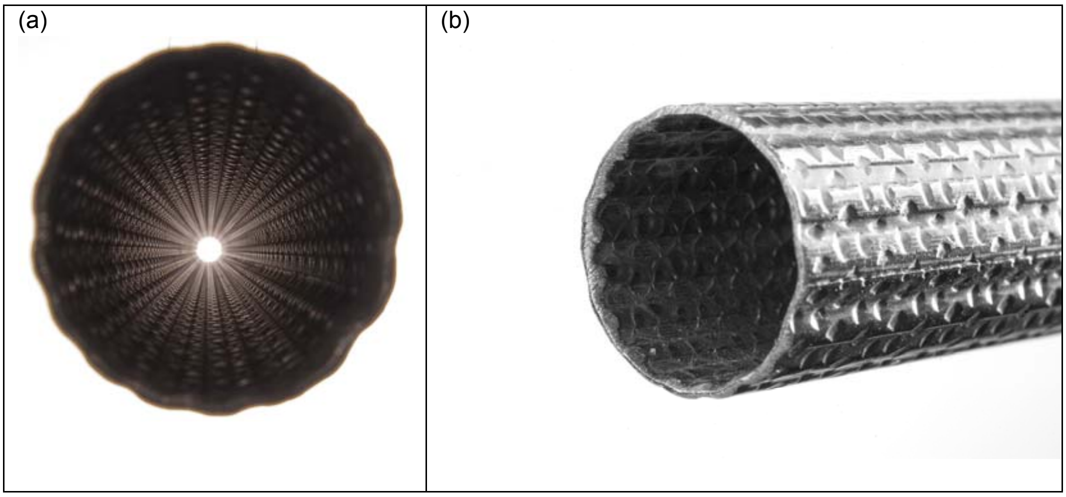


Figure 4 Details of the Vipertex 2EHT (Type 304 L stainless steel) Enhanced Tube (a) Cross sectional inner view (b) Outer surface.

Figures 3 and 4 provide inner and outer surface views of the 0.75 inch (19.05 mm) Vipertex 1EHT and 2EHT enhanced stainless steel heat transfer tubes that were evaluated experimentally in this study. Heat transfer and hydraulic characteristics of the enhanced Vipertex 1EHT heat transfer tubes were evaluated and then verified with a detailed experimental study at the Heat Transfer Research, Inc. (HTRI) Research and Technology Center. The heat transfer experimental setup was a horizontal double-pipe heat exchanger with propylene glycol used for the inside test fluid (for Re between 250 and 18,000 for heating; and between 50 and 20,000 for cooling) and covered a range of annulus Reynolds numbers (Re_A) to approximately 248,000. Kukulka and Smith (2012) presented the results for the heat transfer inside the tube previously; the heat transfer results presented for outside the tube in this study are new. The temperature of the cooling water could be varied between ambient and 250 °F (121.1 °C). For all tests, the heated/cooled length of the tested tube was 15 ft. (4.572 m). Data measurements were performed using multi-point calibrated instruments that when possible have been calibrated to NIST-traceable standards; while other instruments (flow meters, weight scale and pressure transmitters) were factory calibrated, with calibration certificates; multipoint calibration checks are used for verification. Overall error is less than 7%.

Heat transfer and flow enhancement is desired for various conditions. Several new enhancements were considered for the new surface, and modeled in a CFD analysis. The velocity distribution and other heat transfer/flow parameters were evaluated in order to determine the character enhancement that would provide the best performance. Figure 5 provides a sample comparison between an enhanced tube and a smooth tube. It can be seen, from these figures, that the 0.2 inch (0.508 cm) diameter dimple enhancement provides the best velocity distribution of the enhancements considered. As can be seen there is an early onset of turbulent flow with violent mixing occurring within the micro-flows near the wall; this leading to enhanced heat transfer performance when compared to a smooth tube.

Figure 6 shows the velocity distribution of the Vipertex 1EHT enhanced tube (with an optimized enhancement character on a larger section of the tube) that was designed to maximize heat transfer, minimize pumping power and minimize the rate of fouling. Vortex formation, interaction and distribution is studied in this manner. Vortex movement and their location near the tube surface produce the enhanced heat transfer that was verified experimentally in the 1EHT tube.

Single phase, experimental heat transfer evaluations were then carried out on a horizontal tube, for inner fluid heating and cooling, over a range of annulus Reynolds Numbers to ~ 248,000. In all tests, the enhanced tubes outperformed smooth tubes under similar conditions. Performance was evaluated using the enhancement ratio which compares overall performance of the enhanced tube to that of a smooth tube.

Figure 7 shows a comparison of the outside heat transfer for Vipertex 1EHT tubes compared to smooth tubes. When compared to the smooth tube results of Dittus-Boelter (1930) ; there was a heat transfer increase for the Vipertex 1EHT tubes in excess of 250 % for the outside heat transfer coefficient, for Reynolds number (Re_A) flows near 250,000. Figure 8 shows the same comparison, over the same approximate range, for the Vipertex 2EHT tube. For the 2EHT tube the heat transfer increases (when compared to a smooth tube) are in the range of 80 to 120%; however the friction factors are more modest, slightly larger than that of a smooth tube. Other designs provide higher heat transfer values at the expense of increased pumping power and/or an increased expected fouling rate.

Equation (1) relates the heat transfer coefficient, h_o, for the modified Vipertex 1EHT enhanced tube (as shown in Figure 7), to the Reynolds Numbers (Re_A) for outside annulus, water flows:

$$h_o = 0.013\ Re_A^{\ 0.963} \tag{1}$$

with a R-Squared value, $R^2 = 0.982$; where h is the outside heat transfer coefficient (Btu/ hr-ft^2 ^{O}F) and Re_A is the outside annulus Reynolds Number. This equation is valid for water flows with Reynolds Number in the range $30{,}000 < Re_A < 248{,}000$.

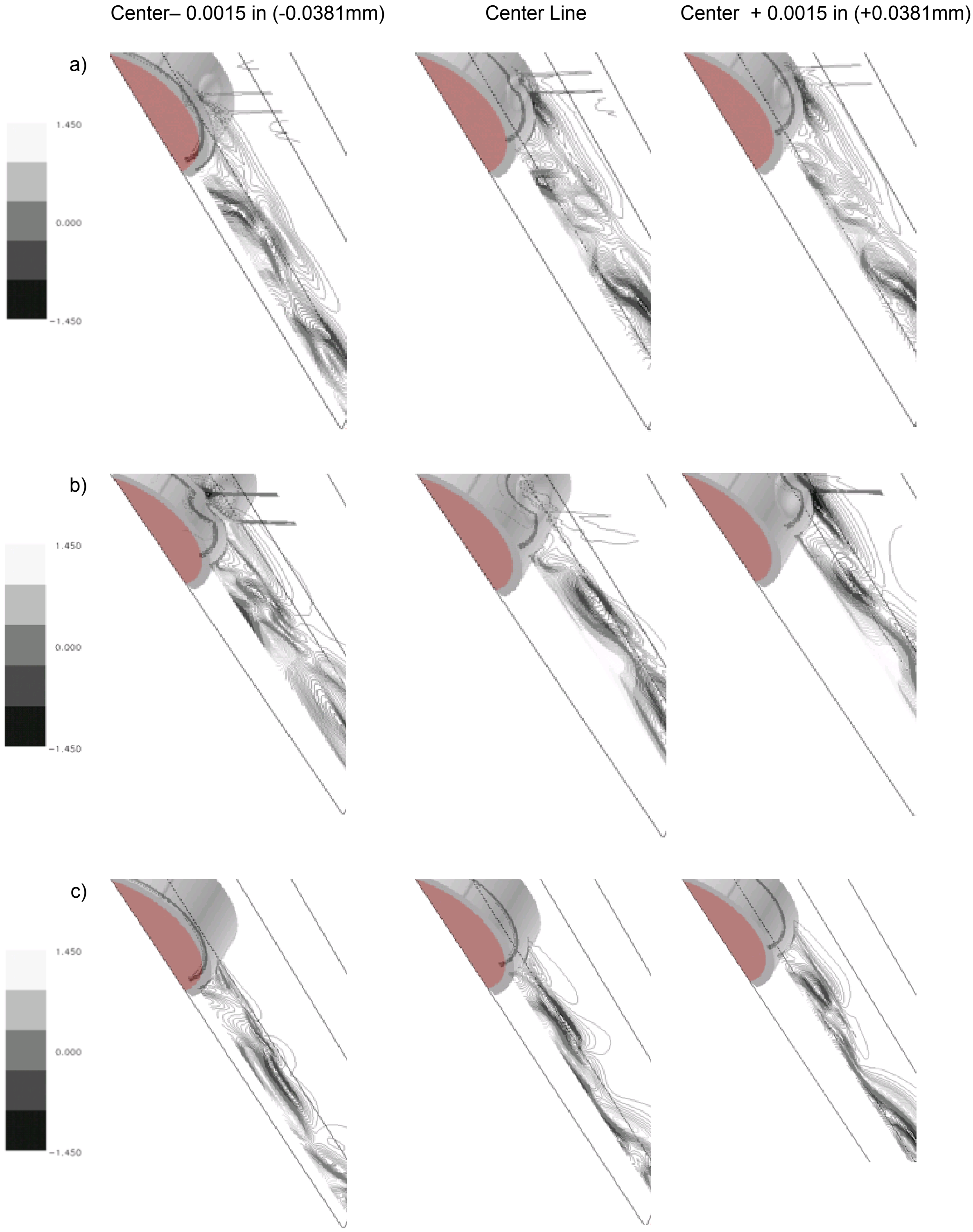
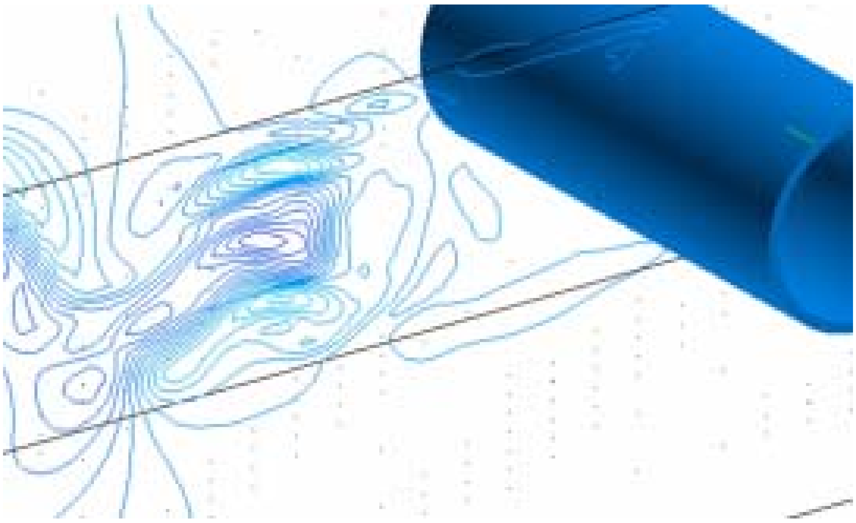
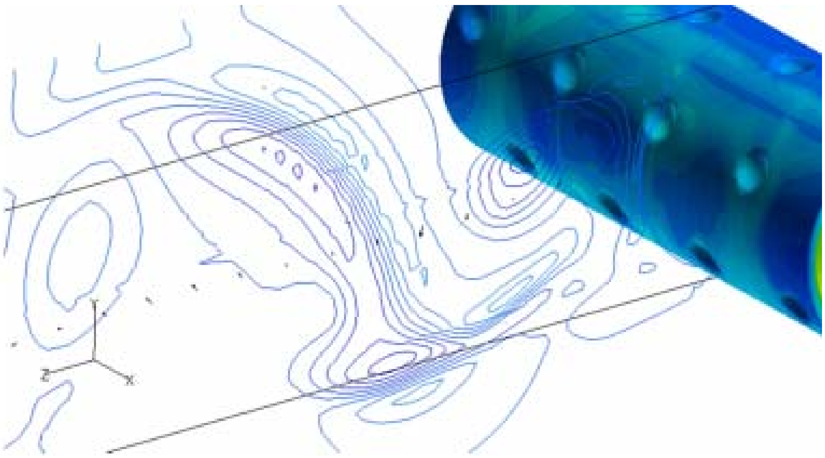


Figure 5: Comparison of the velocity distribution for (a) 0.138 in (0.351 cm) dimple enhancement, (b) 0.2 in (0.508 cm) dimple enhancement, (c) smooth tube, at various locations (enhancement character at centreline and centreline + / - 0.0015 in (0.0381mm) at the same time period and flow conditions.



(a)



(b)

Figure 6: Comparison of the velocity distribution near the outside of a tube for a) Plain unenhanced tube and b) Vipertex 1EHT enhanced tube for the same time period and flow conditions.

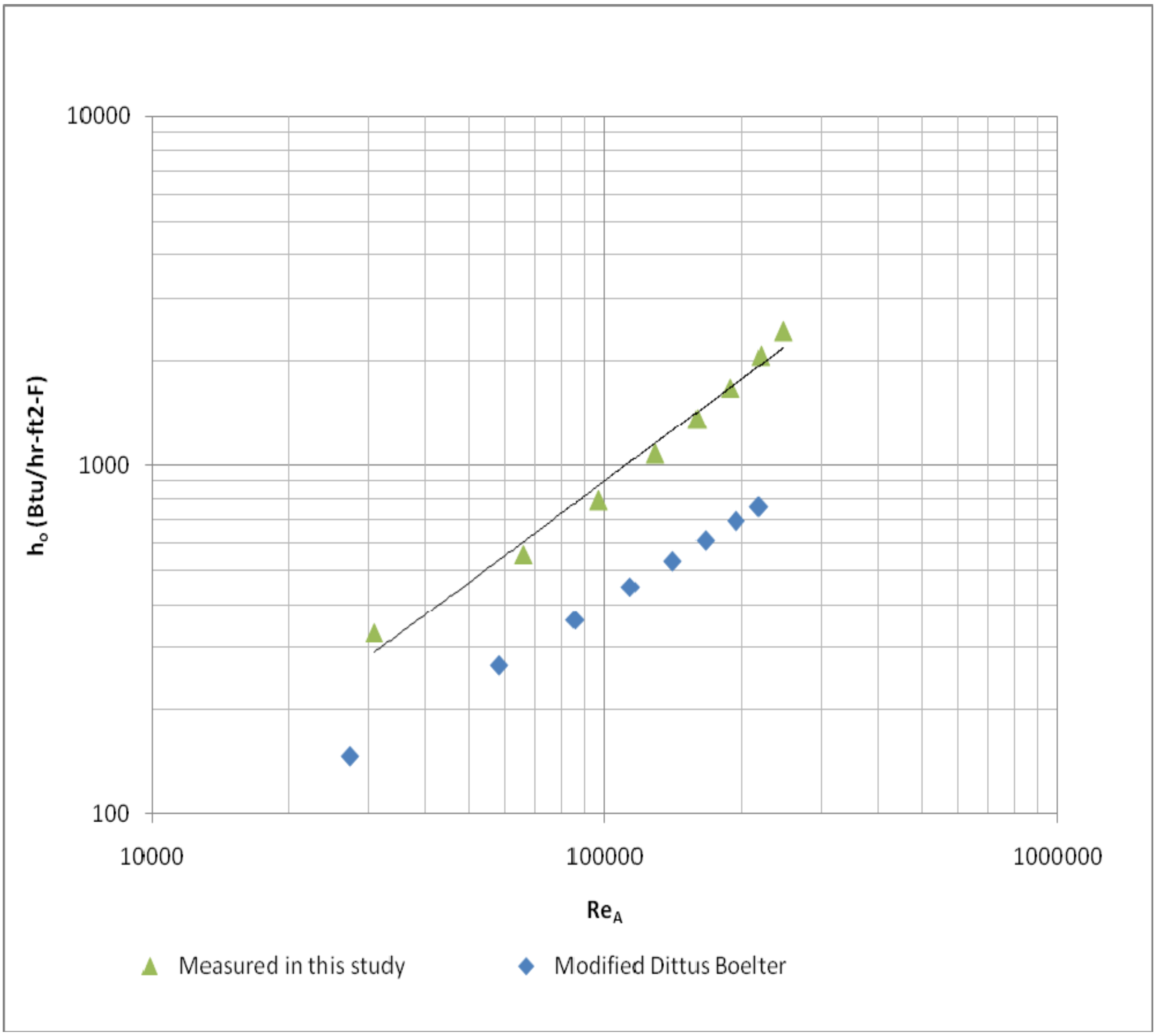


Figure 7: Comparison of the measured outside annulus heat transfer coefficient, h_o, as a function of the annulus Reynolds Number, Re_A, for the Vipertex 1EHT enhanced tube and the smooth tube relation of Dittus-Boelter (1930).

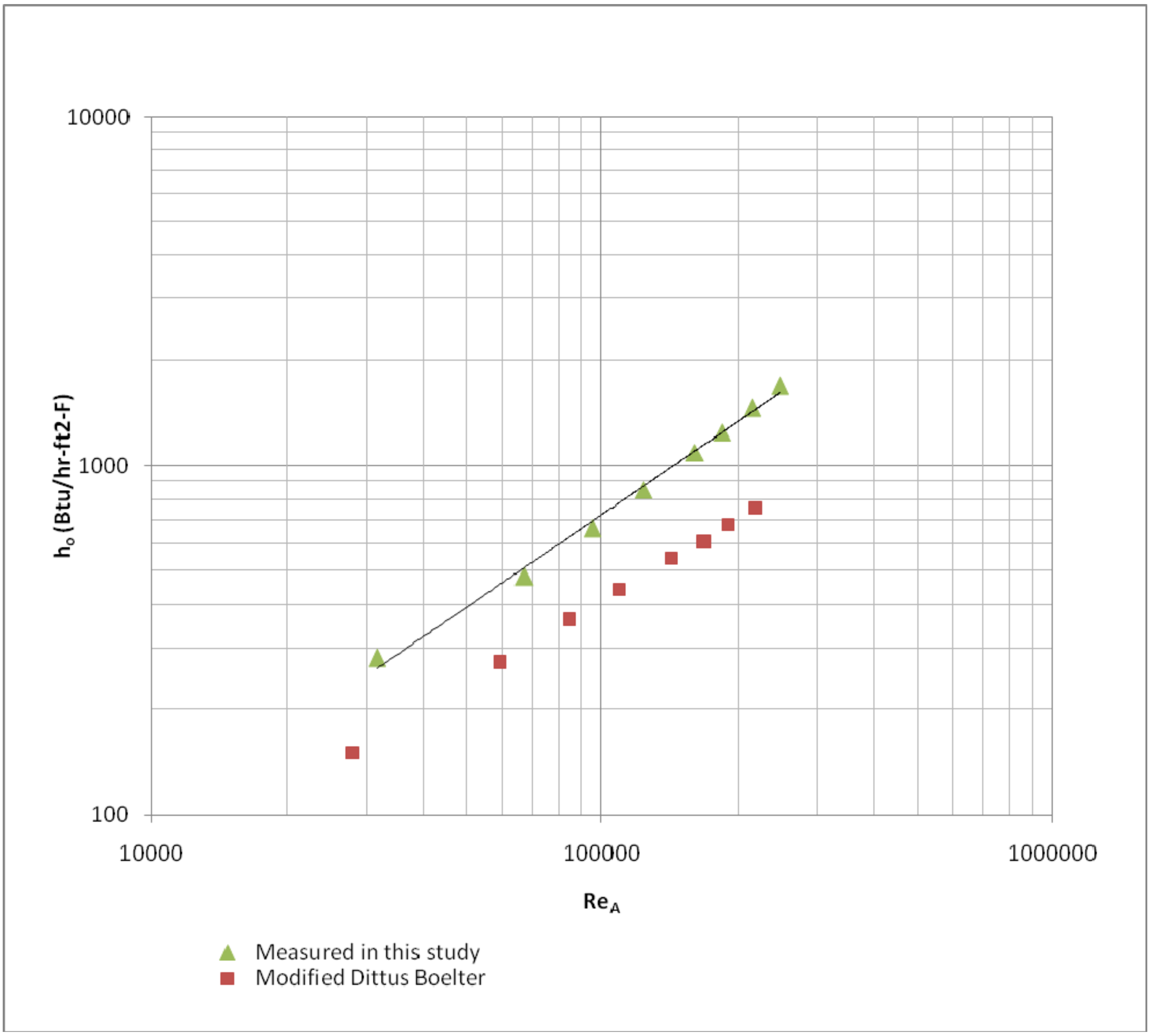


Figure 8: Comparison of the measured outside annulus heat transfer coefficient , h_o , as a function of the annulus Reynolds Number, Re_A , for the Vipertex 1EHT enhanced tube and the smooth tube relation of Dittus-Boelter (1930).

Equation (2) relates the heat transfer coefficient, h_o, for the modified Vipertex 2EHT enhanced tube (as shown in Figure 8), to the Reynolds Numbers (Re_A) for outside annulus, water flows:

$$h_o = 0.028\ Re_A^{0.880} \qquad (2)$$

with a R-Squared value, $R^2 = 0.994$; where h is the outside heat transfer coefficient (Btu/ hr-ft^2 ^{O}F) and Re_A is the outside annulus Reynolds Number. This equation is valid for similar water flows, with Reynolds Number in the range $31,000 < Re_A < 248,000$.

Vipertex 1EHT enhanced heat transfer tubes provide an unusual combination of surface characteristics that produce heat transfer increases on the outside surface of almost 250 % for a small increase in friction factor. Replacing smooth tubes with 1EHT tubes provides the opportunity to cut operating costs and the ability to obtain more heat transfer out of the same equipment footprint.

4. Conclusions

Through the use of computational fluid dynamic methods, optimized three dimensional, enhanced heat transfer surfaces were developed. Vipertex EHT surfaces can be used for a variety of enhanced process applications. This study optimized the development of a new heat transfer surface that was used to enhance the outside heat transfer coefficient. Enhanced surfaces, with a peak performance in the range of Reynolds Numbers (Re_A) from 30,000 to 248,000 are presented. Heat transfer enhancements of almost 250 %, with friction losses less than 100 % were measured with the overall error less than 7%.
All this leads to an important and exciting advancement in system design. The patented Vipertex surface enhances heat transfer, conserves energy and minimizes cost. Additional studies of new Vipertex surfaces are currently under way. Future plans include the study and development of new heat transfer tubes that optimize performance using other design conditions; this will be followed with a detailed experimental study of those tubes.

References

Adaptive Research, 2013, CFD2000, Simunet Corporation, Honolulu, Hi, retrieved April 1, 2013, www.adaptive-research.com.

Agra, O, Demir, H., Atayilmaz, S.O., Kantas, F. and Dalkilic, A.S., 2011, Numerical investigation of heat transfer and pressure drop in enhanced tubes, International Communications in Heat and Mass Transfer, 38, 1384-1391.

Dittus, F. W. and Boelter, L. M. K., 1930, Heat transfer in automobile radiators of the tubular type, U.C. Pub. Eng., 2(13) 443 – 461.

Kukulka, D. J. and Smith, R., 2012, Development and Evaluation of Enhanced Heat Transfer Tubes for Transitional Reynolds Number Flow . Chemical Engineering Transactions, 29(1), 136.

Kukulka, D. J., Smith, R. and Zaepfel,J., 2011, Evaluation of Vipertex Enhanced Heat Transfer Tubes under Fouling Conditions . Chemical Engineering Transactions, 25(1), 665-670.

Kumar, A., Saini, R.P. and Saini J.S., 2012, Heat and fluid flow characteristics of roughened solar air heater ducts- A review, Renewable Energy, 47, 77-94.