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Improving Air-Cooled Condenser Performance Using Winglets and Oval Tubes in A Geothermal Power Plant

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Abstract

Two concepts for improving the heat transfer performance of the air-cooled condensers used in binary geothermal power plants are being developed and tested at the INEEL. These concepts involve (1) replacing the circular tubes with oval tubes and (2) adding strategically located vortex generators (winglets) in the fins. These concepts can be used individually or in unison. Depending on the various design parameters, the heat transfer coefficient can be enhanced by 25–35%, with a minimal increase in pressure drop. The INEEL is also collaborating with several manufacturing companies to improve and commercialize these concepts. This paper summarizes the work completed to date and plans for the future.

Keywords: air-cooled condensers, heat transfer enhancement, oval tubes, vortex generators

Introduction

In a binary geothermal plant where there is not a sufficient supply of water for an evaporative cooling system, heat must be rejected to atmospheric air. This heat rejection is accomplished through the use of large air-cooled condenser units in which air is forced through several rows of long individually finned tubes by large fans. The cost of the air-cooled condenser in a typical binary geothermal power plant represents about 20 to 35% of the total plant cost. The condenser tubes have fins on the outside surface in order to provide a large effective heat transfer surface area. Improving the air-side heat transfer coefficient is expected to result in smaller, more efficient heat exchangers and reduced plant cost.

Another requirement of a heat transfer enhancement device is that it should not significantly increase the heat exchanger pressure drop since the power required to operate the fans represents a significant parasitic house load, reducing the net power production of the plant

INEEL researchers are investigating improving the condenser performance by incorporating one or both of the following two concepts. The first concept is to add properly sized and strategically located vortex generators/winglets on the fins. The second concept is to replace the circular tubes with oval tubes. Deployment of winglets on fin surfaces has been shown to enhance heat transfer through the generation of longitudinal vortices that produce localized thinning of thermal boundary layers. Jacobi and Shah [1] provide an excellent review of heat transfer enhancement through the use of longitudinal vortices. The usage of oval tubes instead of circular tubes results in reduced form drag and increased tube-surface area for the same cross-sectional internal flow area. This strategy is not practical in all cases due to manufacturing considerations and the fact that circular tubes are inherently stronger and can therefore withstand much higher pressures with the same wall thickness. In geothermal power plants, air-cooled condensers operate at relatively low pressure, so oval tubes can be considered.

The INEEL has been performing research on these concepts for the past two years. A delta winglet (a triangle on its longer side) or a rectangular winglet are the preferred shapes for the present investigation. By optimizing the shape and location of the winglets, the resulting vortices can minimize the size of the wake (stagnant flow) region behind a cylindrical tube and also improve the heat transfer downstream of the winglets. Experiments have shown that it is reasonable to expect an improvement of ~20-35% in heat transfer coefficient by adding the winglets. Additional experiments have been performed to obtain pressure drop measurements in several laboratory-scale model cases of tube bundles with and without winglets. Considering the heat transfer enhancement and pressure drop results, one or more desirable prototype cases will be chosen for further research. It is anticipated that by combining both concepts, the air-side heat transfer coefficients in binary plant air-cooled condensers can be increased without imposing additional pressure drop and fan power. This paper provides up-to-date progress of our work including some of our work published elsewhere [2-5] and presents an outline of future efforts.

Theoretical Background

Jacobi and Shah [1] have provided fundamental background about the generation of longitudinal vortices. Longitudinal vortices are generated naturally in fin-tube heat exchanger passages by the interaction of the flow velocity profile with the heat exchanger tube. These naturally occurring vortices are called horseshoe vortices. Vortices can also be generated if the flow is interrupted by vortex generators, small winglets placed in the flow path. The size, shape, and angle of attack of the vortex generators determine the specific characteristics of the vortices generated in the flow. These vortices lead to enhancement of heat transfer. Unfortunately, vortex generators also lead to increased form drag and wall shear, which leads to increased pressure drop even though heat transfer and pressure drop are not directly related. If the tubes are made of oval shape with major axis being parallel to the flow direction, tube-related form drag is reduced significantly, leading to lower overall pressure drop. To take advantage of these phenomena and develop an acceptable practical design, the INEEL has been performing experimental and modeling research. This paper summarizes some of the important results of the experimental research.

Experimental Investigation

Beginning in 1999, the INEEL performed a series of laboratory-scale experiments to systematically evaluate the influence of vortex generators and oval tubes on heat transfer enhancement and changes in pressure drop. This paper summarizes salient results of these experiments. The details about the experiments and these data have been provided in other publications [2, 3, and 5]. A brief summary of the experimental set-up shown in Figure 1, is provided here. The single-tube heat transfer experiments were performed in a narrow rectangular flow channel designed to simulate a single passage of a fin-tube heat exchanger. A schematic of the flow loop is shown in Figure 1. The flow channel has the dimensions of height = 1.016 cm and width = 11.25 cm (0.4 in. x 4.5 in.). The duct was fabricated primarily out of lexan polycarbonate. The test section length was 27.94 cm (11.0 in.), yielding L/H = 27.5. A flow development section with L/H = 30 was located upstream of the test section. Consequently, depending on Reynolds number, the flow is approximately hydrodynamically fully developed as it enters the test section. Either a single cylinder having a diameter of 5.08 cm or a single elliptical tube with major axis of 8.80 cm and an aspect ratio of 3:1 was located in the center of the test flow channel. The triangular (delta) winglets had a 1:2 height/length aspect ratio and were oriented at either a 45° angle (for a circular tube) or a 30° angle (for an oval tube) to the flow. The height of the winglets was 90% of the channel height. To thermally visualize the test section bottom surface (representing the fin surface), the top wall of the flow duct in the vicinity of the circular tube was formed by a calcium fluoride (CaF_2) window with dimensions: 12.7 x 12.7 x 0.6 cm (5.0 x 5.0 x 0.24 in.). The CaF_2 windows enabled viewing of test section bottom surface (representing the fin surface) with an imaging infrared camera. The transmissivity of the CaF_2 window is very high (>95%) in the camera wavelength range of sensitivity of 3.6-5.0 μm.

The test section bottom surface (polycarbonate) was painted black using ultra-flat black paint in order to achieve a surface emissivity very close to 1.0.

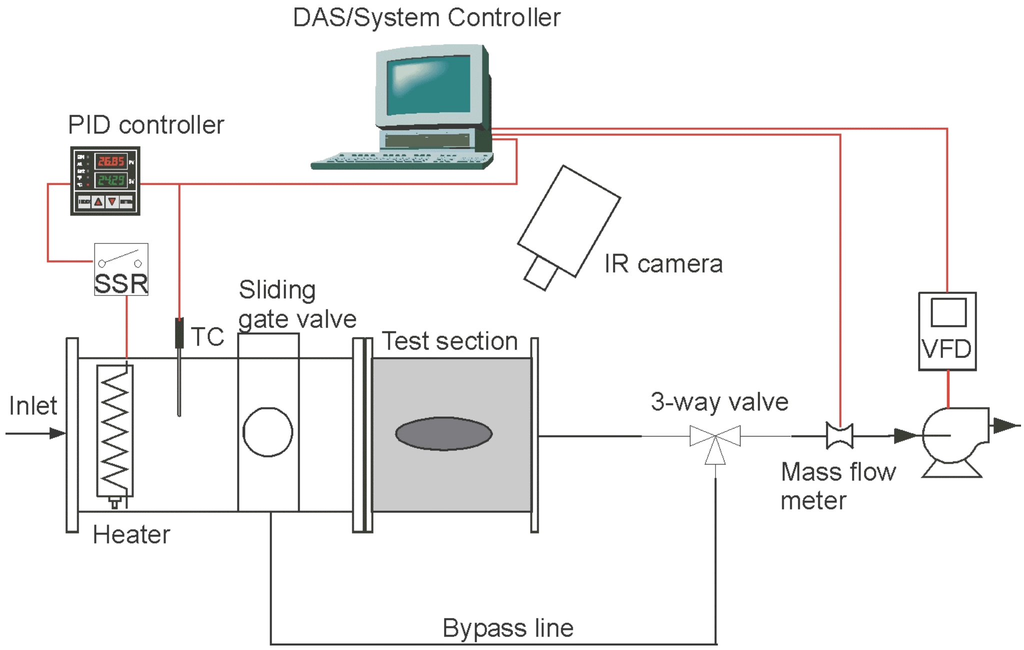

Figure 1. Schematic of flow loop.

A transient heat transfer measurement technique was employed for obtaining detailed local heat transfer measurements on the model fin surface. Inlet air is heated to a desired setpoint temperature using an in-line feedback-controlled finned-element air heater (350 W). The heated air initially flows through a bypass line until the desired air temperature and flow rate is established. The air is then suddenly diverted through the test section by changing the position of a 3-way valve. Using this technique, the room- temperature fin/tube model is suddenly exposed to a uniformly heated airflow, initiating a heat conduction transient in the lexan substrate. Local surface temperatures on the substrate increase at a rate that is dependent on the value of the local heat transfer coefficient. This transient localized heating is quantitatively recorded using an imaging infrared camera. Values of local heat transfer coefficients can then be determined from an inverse heat conduction analysis. The bottom lexan surface is assumed to behave like a one-dimensional semi-infinite solid undergoing a step-change in surface heat transfer coefficient. This assumption is valid for a time period of ~88 s after initiation of the transient.

Results

Two local surface heat transfer coefficient contour plots obtained using the imaging infrared camera are presented in Fig. 4. The image on the left side represents local heat transfer for flow around a circular tube without winglets. The image on the right side includes the effects of winglets. The addition of winglets yields a reduction in the size of the low-heat-transfer wake region and also provides localized heat transfer enhancement in the vicinity of the winglets. Peak local heat transfer coefficients in the vicinity of the winglets are similar to the peak values observed in the cylinder stagnation region. This figure represents a direct comparison of local heat transfer distributions for a circular cylinder with and without winglets at Re_H~1200.

The comparison reveals that, for this winglet location, the horseshoe vortex produced by the interaction of the flow with the circular cylinder is disrupted by the winglets. There is a reduction in the width of the low-heat-transfer wake region, but the heat transfer coefficients directly downstream of the cylinder are actually slightly reduced for the winglet case compared to the no- winglet case. Stagnation-region heat transfer coefficients are slightly higher for the winglet case compared to the no-winglet case.

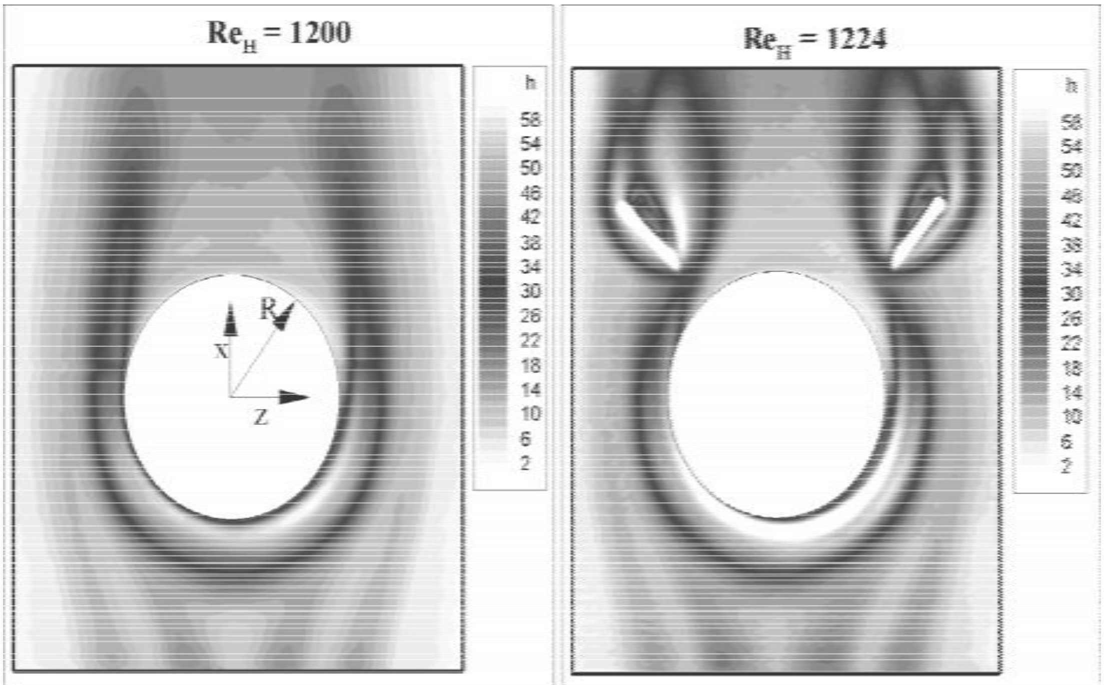

Figure 2. Direct comparison of local heat transfer distributions for a circular cylinder with and without winglets.

A plot of the spanwise variation in local wake-region heat transfer coefficient at an axial location just downstream of the winglets is presented in Figure 3 for the same two data sets presented in Fig. 2. The spanwise variation for the winglet case clearly shows a double peak associated with each winglet. A single peak associated with each horseshoe vortex is evident in the no-winglet curve.

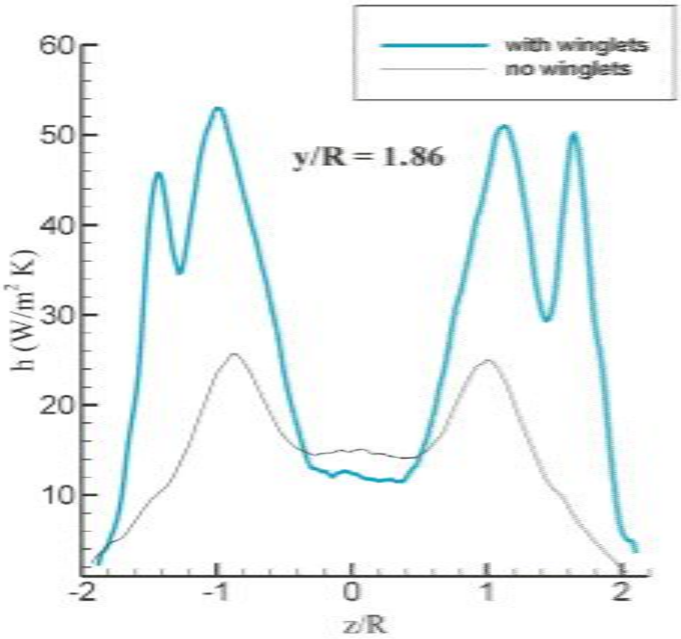

Figure 3. Spanwise variation in local wake-region heat transfer coefficient, with and without winglets.

Mean fin-surface heat transfer coefficients have been calculated based on the local heat transfer results for the seven flow configurations studied to date (two detailed in this paper plus five detailed in refs [2-5]). For these calculations, only the active fin area is considered. The areas covered by the tubes (circular or oval) or the winglets are not included. Results of these calculations are presented in Fig. 4 in the form of Nusselt number based on channel height, Nu_H, versus Reynolds number based on channel height, Re_H. A small schematic of each flow configuration is shown in the top of the figure. Highest mean heat transfer coefficients were observed for the case of a circular tube plus winglets with the winglets located on the downstream side of the cylinder, oriented at a 45□ angle to the flow (right side of Fig. 3). The cases of oval tube plus one pair of winglets and oval tube plus two pairs of winglets yielded similar mean heat transfer results, with the single-winglet-pair configuration actually producing higher heat transfer at the highest Reynolds numbers. The addition of the single winglet pair to the oval-tube geometry yielded significant heat transfer enhancement, averaging 38% higher than the oval-tube, no- winglet case. Mean Nusselt numbers for the cases of a circular tube without winglets and a single delta-winglet pair with no tube yielded similar results. Heat transfer results for the oval tube without winglets were quite low. Lowest heat transfer coefficients, as expected, were produced by the open-channel configuration.

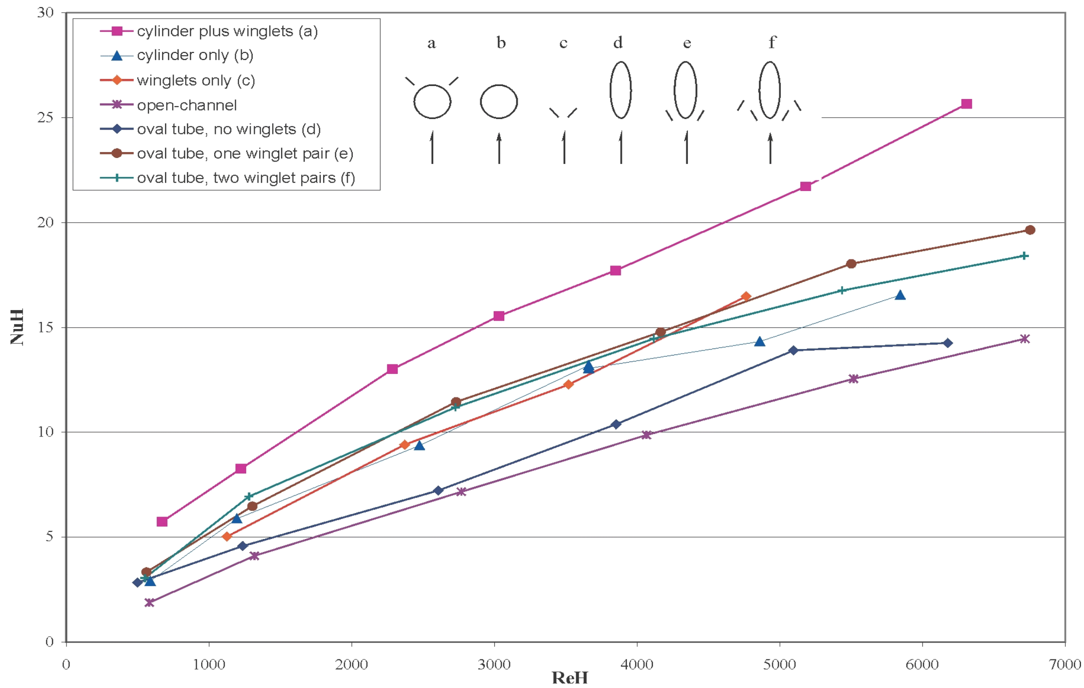

Figure 4. Mean fin-surface Nusselt numbers for seven flow configurations, based on local heat transfer results.

In order to fully assess the performance of any of these flow configurations, the pressure-drop behavior must be also considered. Results of the pressure-drop measurements are presented in Fig. 5 in terms of friction factor versus Reynolds number based on hydraulic diameter (Re_{Dh}). Based on this definition, the highest friction factors were observed for the case of the circular tubes with winglets (case (a) in the figure). This case also yielded by far the highest heat transfer coefficients. Next highest friction factors were observed for the case of circular tubes without winglets. Friction factors for the elliptical- tube cases were lower than the circular-tube friction factors by a factor of 2 or 3, depending on Reynolds number. In fact for Reynolds numbers lower than approximately 800, the oval-tube friction factor values were lower than corresponding open-channel friction factors. This is due to the fact that, for a specified total duct flow rate, the mass flux values associated with the oval-tube array are much higher than the open-channel mass-flux values. Therefore, since the oval tubes have low form drag, and the friction factor definition has air flow mass flux in the denominator, the oval-tube friction factor values are lower than corresponding open-channel values. In order to check the validity of our friction factors, an open channel was fabricated and tested. These open-channel results are also shown in Fig. 10. At low Reynolds numbers, The measured open-channel friction factor values tend to be parallel to, but slightly higher than, the theoretical value of $24/Re_{Dh}$ for flow in a parallel-plate channel. At the highest Reynolds numbers, the open-channel and oval-tube data agree well with the Petukov [6] correlation for turbulent- flow friction factor.

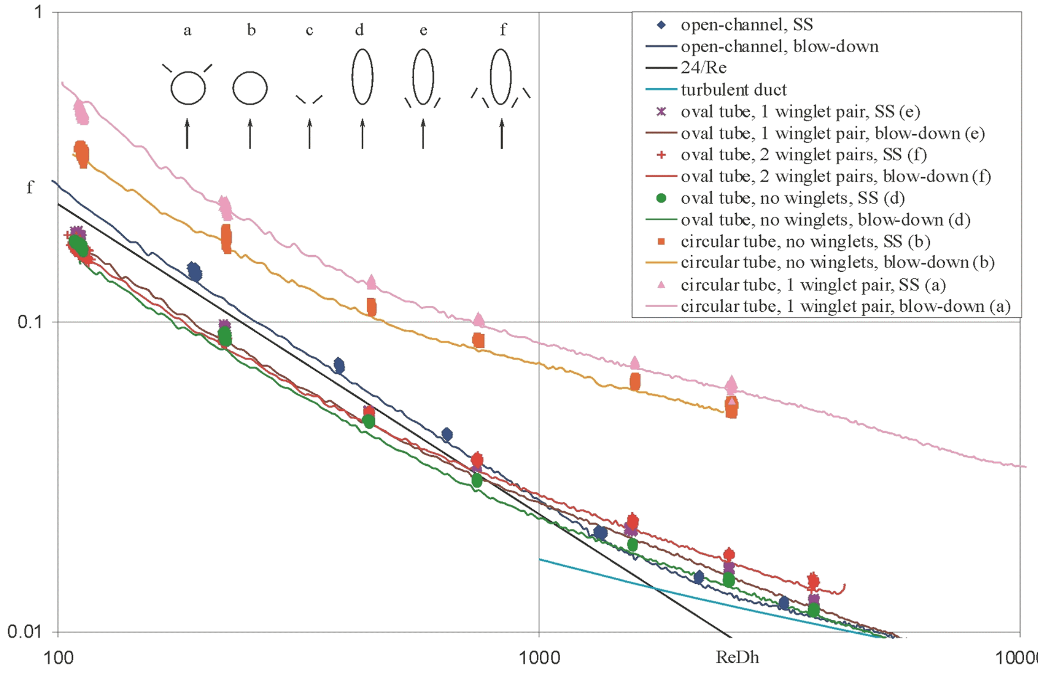

Figure 5. Friction factors measured for seven flow configurations, steady-state and blow-down results.

Industrial Collaboration

To commercialize the proposed concepts, several practical hurdles have to be overcome. Therefore, the INEEL is also actively involved in collaborative effort with several tube and condenser manufacturers. The INEEL is entering into formal agreements with the industrial companies to transfer the technology and seek their input for further development. These efforts are progressing in parallel to the ongoing research. The objectives of the industrial collaboration are to: (a) develop the tube bundle design for an optimum enhancement of heat transfer and minimize the pressure drop; (b) develop fabrication techniques to economically manufacture the tubes with winglets; (c) minimize fouling potential of the enhanced tubes; and (d) on-site testing of an enhanced tube bundle. It is hoped that our work during the current and next fiscal year will answer some of these issues. Considering enhancement of heat transfer, changes in pressure drop and manufacturing costs, it is hoped that the overall benefits of the proposed system may be ~20% higher. However, an accurate estimate of the benefits can be made only after having an industrial partner and assessing the marketability. Some options of fabrication for adding the vortex generators are being considered. Presently, Hudson Products Company, Houston, TX and McElroy Manufacturing Company, Tulsa, OK have provided finned tubes for prototype testing. Fabrication of finned oval tubes and economic fabrication of finned tubes with winglets are other pending issues. Currently, we are negotiating with a few companies to gauge their interest and capabilities to manufacture and market the proposed concept.

International Collaboration

We have also obtained funding from New Energy and Industrial Technology Development Organization (NEDO) of Japan. Under this grant, we are collaborating with two other researchers on fundamental issues of enhancement heat transfer using vortex generators. These collaborators are Prof. K. Torii of Yokohama National University, Yokohama, Japan and Prof. G. Biswas of Indian Institute of Technology, Kanpur, India. Their research also helps us in making decisions regarding optimum design of the enhanced tubes.

Conclusions

Laboratory-scale experiments have been conducted for measuring heat transfer coefficient corresponding to circular and oval tubes with and without vortex generators. All the data indicate that the addition of winglets increases the heat transfer coefficient by ~35% as compared to plain tubes. Corresponding increase in friction factor is in the range 5–10% for Reynolds number, Re_{Dh} in the range 500–5000. Next, prototype-scale tube bundle tests will be performed. Meanwhile industrial collaboration for developing an economic manufacturing method is continuing.

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