Applied Mechanics and Materials Vol 15 (2009) pp 41-46
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doi:10.4028/www.scientific.net/AMM.15.41

Effect of Maximum Temperature and Heating-Cooling Repeated Cycles on Thermal Contact Resistance of a Composite Tube

I. Carvajal Mariscal[a], F. Sánchez Silva[b], G. Polupan[c], J. A. Basualdo Rojo[d]

Instituto Politécnico Nacional, SEPI ESIME, Edificio 5, 3er piso UPALM,
07738 México D.F., México

[a]icarvajal@ipn.mx, [b]fsnchz@yahoo.com.mx, [c]gpolupan@ipn.mx, [d]basuck10@yahoo.com.mx

Keywords: composite L-type finned tube, thermal contact resistance, operational parameters.

Abstract. Experimental research results of the operational parameter effect on Thermal Contact Resistance (TCR) in a copper-aluminum L-type finned tube are presented. The investigated operational parameters were the maximum operational temperature and the number of repeated heating-cooling cycles. The TCR was experimentally determined by measuring the total heat supply, core tube wall and inner fin surface temperatures for steady-state and natural-convection conditions. In addition, the specimen was tested through up to 200 heating-cooling cycles. The experimental results showed a TCR increase of 81% at the same time as the average temperature difference between the hot inner flow and cooling air increased from 30°C to 130°C; over the maximum operational temperature (120°C), the TCR increased faster than before; and, after the heating-cooling cycle testing the TCR presented an increase of 31% in respect with the initial value. Such findings may be useful as a reference for preliminary thermal design and as recommendations for optimal operation of heat exchangers based on copper-aluminum L-type finned tubes.

Introduction

Air-cooled heat exchangers are used in refineries, at compressor stations, in petrochemical and gas-processing industries, in thermal power stations, as well as in large refrigerating plants and in air conditioning systems. In most air-cooled heat exchangers the elements of the heat-transfer surfaces are composite finned tubes.

These composite finned tubes generally have aluminum fins mechanically coupled with a core tube that can be made of different materials (steel, copper, or aluminum). Fins can be attached using various technologies depending basically on the maximum operational temperature the tubes will have to withstand. For the highest temperature, up to 400 °C, a G-type finned tube with a metal strip embedded in a core tube groove is used. An E-type composite finned tube obtained with cold rolled extrusion technology is recommended for temperatures up to 310° C. The KL-type fin attachment, with a wound metal strip and a core with knurled surface, and the L-type (Fig. 1), with a wound metal strip on the core, are recommended for temperatures up to 250° C and 120°C, respectively [1].

Because of their relatively low cost, the L-type finned tubes have been widely used in the production of air-cooled heat exchangers. However, because of the imperfect contact at the fin-tube interface, the Thermal Contact Resistance (TCR) can be appreciable in this type of tubes [2].

In contrast to numerous investigations on TCR in plane joints, experimental and analytical studies concerned with cylindrical joints, such as in composite finned tubes, are limited [3]. At present, the experimental investigations on TCR in composite finned tubes concentrate on characterization of the thermal behaviour and pressure drop of banks of tubes with different fin types and the effect of the TCR in these surfaces.

Kuntysh and Stenin [4] investigated the effect of fin height change on the contact pressure between the steel pipe surface and the surface of an aluminum shell in composite finned tubes. An approximate method for determining the TCR for this type of tubes was developed. To use this method, the maximum height of the micro-roughness of the contacting surfaces has to be known. Piir et al. [5] investigated the thermal and aerodynamic characteristics of composite (steel-aluminum) KL-type finned tube banks. They state that a one-time increase in the effective temperature of a steel bearing tube did not manifest a significant irreversible change in the TCR of this kind of tubes. Kuntysh [6] characterized bundles of composite L-type finned tubes with different fin pitches. Comparison between different bundles confirms that it is best to use a smaller pitch for the L-type fins. Kuntysh also determined how the oil film, in the zone of contact between the foot of the L-type fins and the surface of the bearing tube, affects the heat transfer. He reported that the oil evaporated completely at 120-130 °C and that the absence of oil on the outer surfaces of the fins did not affect the heat transfer. Piir et al. [7] studied the effect, on the thermal contact resistance of composite G- and KL-types finned tubes, on repeated cycles of heating to 270ºC and cooling to 50 °C. It was found that the heating–cooling cycles increase the TCR of these tubes in the cold state by factors between 1.5–2.5. However, from the above-mentioned studies, it can be noted that the effect of such important operational parameters as maximum operational temperature and heating-cooling cycles on composite L-type finned tubes have not been studied.

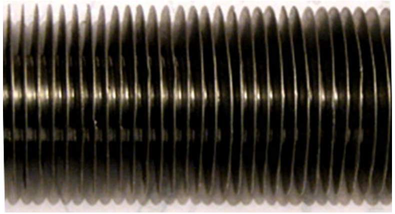

Fig. 1. L-type finned tube

This work provides an experimental investigation of most important operational parameter effect on the TCR in a copper-aluminum L-type finned tube.

Experimental Investigation

This experimental research had two main objectives: first, to determine the TCR in a copper-aluminum L-type finned tube and, second, to investigate the effects of maximum operational temperatures and repeated heating-cooling cycles on the TCR.

Experimental Rig. The experiments were carried out in a wind tunnel that has a 0.04×0.02 m cross section test zone (Fig.2), in which it was placed, horizontally, one composite L-type finned tube. The wind tunnel has two axial fans that provide an air flow with a velocity of up to 15 m/s.

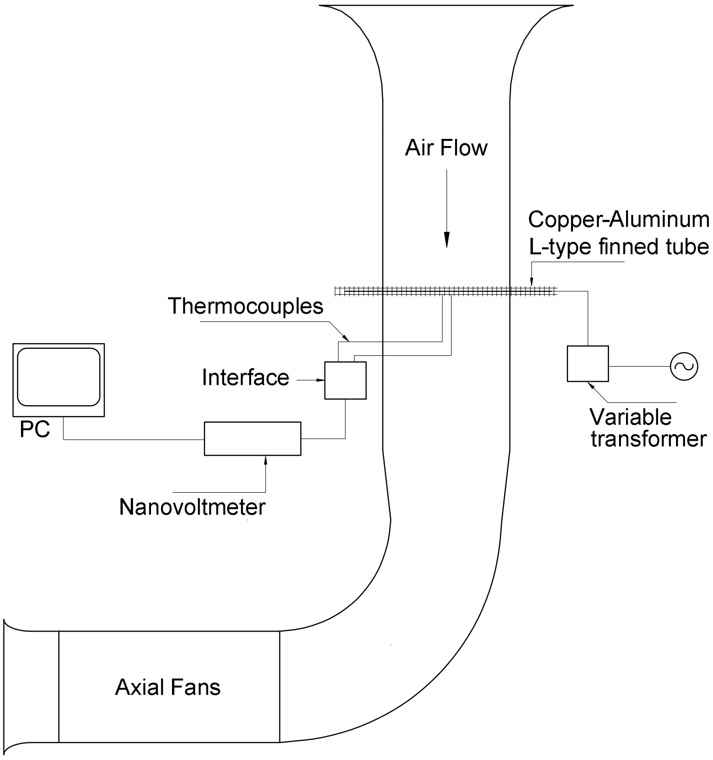

Fig. 2. Schematic diagram of the experimental apparatus

A standard composite L-type finned tube with a copper core tube and a wound aluminum strip was used. Its geometrical dimensions are the following: core tube inner diameter d_{in}=0.0138 m; core tube external diameter d_{ex}=0.016 m; fin diameter D_{fin}=0.038 m; fin pitch s_{fin}=0.002 m; fin thickness e_{fin}=0.0005 and length L = 1 m.

The heat flow was generated by an electrical resistance. Its geometrical and electrical parameters are the following: length $L_{ER} = 0.04$ m; diameter $d_{ER} = 0.0127$ m; resistance $R = 20\ \Omega$, and electrical power $P = 1.1$ kW for a supplied voltage of 127 V. The electrical resistance was installed in the core tube; the interstice between the electrical resistance and the inner surface of the core tube was filled with magnesium oxide. The heat flow was regulated using a variable transformer (0-160 V) connected directly to the electrical resistance. A voltmeter and ammeter were used to measure the supplied voltage, V, and current, I, respectively. The finned tube ends were isolated in order to decrease the heat losses, which were estimated to be less than 4 %.

To determine the TCR, measurements were carried out for steady-state and natural-convection conditions for a heat flow supply from 20 to 200 W, which corresponds with a core tube external surface temperature of 55 and 155 °C, respectively (18 sets of temperature readings in total). At the same time, this research also considered the effect of maximum operational temperature over the recommended temperature of 120 °C. Moreover, to study the effect on the TCR on repeated heating-cooling cycles, the composite tube was heated from 20 to 160 °C and cooled by an air stream with a velocity of 14 m/s in each cycle. After each of the 25 heating-cooling cycles, the TCR was measured; 200 results for the heating-cooling cycles were obtained. In all experimental tests, the average temperature of the cooling air was 24 °C.

Temperature Measurement and Uncertainty. To measure the temperatures of the tube external surface and the internal fin surface, eighteen T-type thermocouples were used. They were calibrated taking as standard a resistance temperature platinum detector of high accuracy, the ‘‘F250 Precision Thermometer.” The calibration was carried out, following recommendations from the norm ASTM E-237, for 25 °C to 150 °C in 25 °C increments.

These eighteen thermocouples were divided into three groups, one of them located at the centre point in the tube’s length and the other two 0.1 m on either side of that point. Each group had three pairs of thermocouples, which were located around the tube on specific positions (Fig. 3). Of each pair, one thermocouple was fixed at the core tube wall and the other at the inner fin surface. The thermocouples were all connected through an interface to a nanovoltmeter, “Guildline 4880A,” and from it to a computer to log the data.

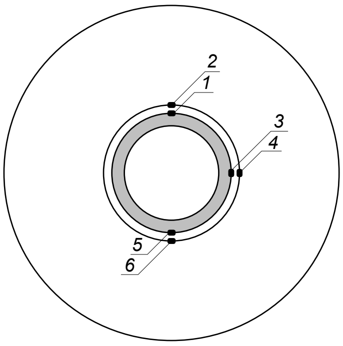

Fig. 3. Location of thermocouples on the specimen

The electrical power, P, was calculated using the well-known formula

$$P = VI\ , \tag{1}$$

where V and I are voltage and electrical current, respectively.

Due to the Joule effect, the heat input was estimated to be equal to the electrical resistance power P. Considering the heat losses of the tube ends, being Q_{loss}, the total heat flow, the Q_{tot}, dissipated from the core tube surface is

$$Q_{tot} = P - Q_{loss}\ . \tag{2}$$

The thermal contact resistance, R_c, was determined by the following equation:

$$R_c = \frac{A_c(\bar{T}_t - \bar{T}_f)}{Q_{tot}}, \tag{3}$$

where A_c is the contact area; $\bar{T}_t$ and $\bar{T}_f$ are the average temperatures of the external core tube and inner fin surfaces, respectively.

For different heat flow values, the average temperature in the contact zone, $\overline{T}_{cz}$, was obtained using the formula

$$\overline{T}_{zc} = 0.5(\overline{T}_t - \overline{T}_f)\ . \qquad (4)$$

After calibration, the average uncertainty of all thermocouples resulted to be 0.1 °C. To calculate the average uncertainties in the total heat flow, Eq. (2), and thermal contact resistance, Eq. (3), the law of propagation of uncertainties described in [8] was applied; it resulted to be equal to±8.18% and ±7.42%, respectively.

Results

The results were used to plot the thermal contact resistance R_c versus the total heat flow supplied Q_{tot} (Fig. 4). TCR increases from 0.00011 m^2K/W to 0.00058 m^2K/W, an increase of 81%, as Q_{tot} increased from 20 to 200 W. The average TCR was 0.00033 m^2K/W in the test range.

To analyze the effect of the maximum operational temperature, a R_c versus $\overline{T}_{cz}$ graph was used (Fig. 5). The test range can be divided into two zones: before and after 120 °C (393 K), which is the recommended maximum operational temperature of composite L-type finned tubes [1, 6]. From Figure 5, it can be seen that after $\overline{T}_{cz}$ = 120 °C (393 °K), the TCR increases faster than before. This faster increase in the TCR could be the result of the release of the contact pressure between the copper tube and the aluminum fin, which could be evaluated by the increment of the temperature difference, ΔT_S, between these surfaces (Fig. 6). The release of the contact pressure probably was caused by the different expansion coefficients (aluminum $23.1 \times 10^{-6}\ K^{-1}$; copper $16.1 \times 10^{-6}\ K^{-1}$ [9]) of the two surfaces. This finding indicates that the operation time, over the maximum operational temperature (T_{max} = 120 ºC (393 °K)), has to be reduced for air-cooled heat exchangers made of copper-aluminum L-type finned tubes.

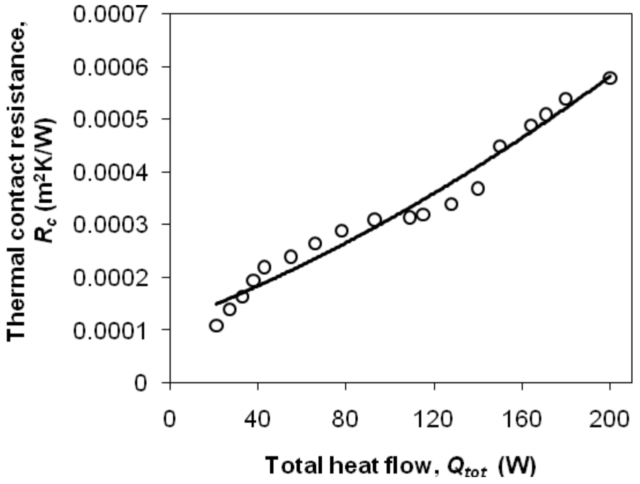

Fig. 4. TCR behavior in a copper-aluminum L-type finned tube

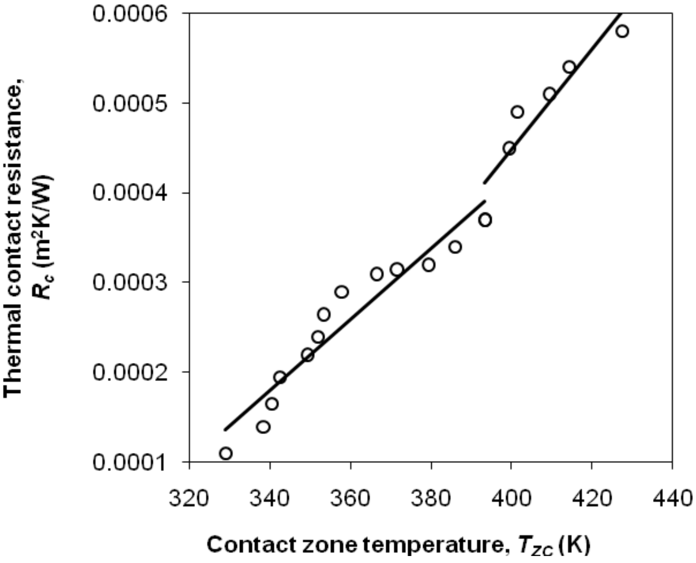

Fig. 5. Effect of maximum operational temperature on TCR

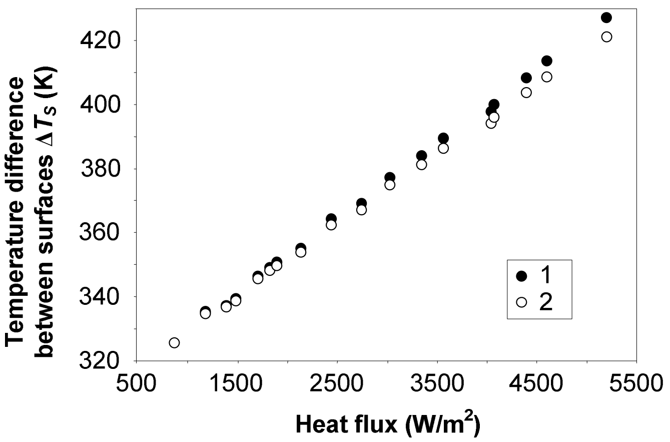

Fig. 6. Temperature difference between copper tube (1) and aluminum fin (2).

Repeated heating-cooling cycle experimental results are shown in Fig. 7, in which each marker represents a certain number of cycles from 25 to 200. For a heat flow supply of 20 W, the TCR increases from 0.00014 m^{2}K/W to 0.000275 m^{2}K/W, as the number of cycles increases from 25 to 200. For the same increment of cycles but with a heat flow supply of 200 W, the TCR increases from 0.00056 m^{2}K/W to 0.00074 m^{2}K/W. After 200 heating-cooling cycles, the average TCR was 0.00048 m^{2}K/W. This finding represents an increase of 31% in respect with the initial value (0.00033 m^{2}K/W) before the heating-cooling testing. This result is lower than the values obtained for G- and KL-types finned tubes after a similar testing [7], which is probably due to a higher maximum temperature, 270 °C, used in those tests in comparison with 160 °C used in the present work. In many industrial processes, the air-cooled heat exchangers operate only 8 hours a day, five days a week, meaning that they have 240 heating-cooling cycles per year. Therefore, in only one year, the equipment's thermal efficiency could be seriously reduced because of the TCR increment caused by the heating-cooling cycles.

It has to be noted that the above-mentioned experimental results are valid only for the tested copper-aluminum L-type finned tubes because the manufacturing processes of this kind of tubes can vary elsewhere. However, they may be useful, especially those TCR values for a core tube external surface temperature between 55 and 155 °C, as a reference for preliminary thermal design of heat exchangers based on copper-aluminum L-type finned tubes.

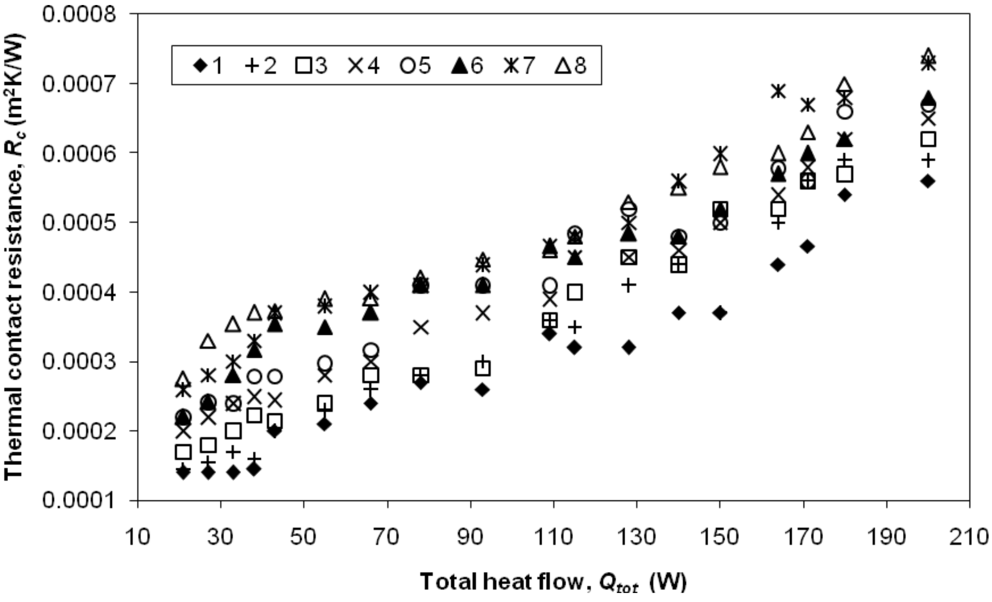

Fig. 7. Effect of heating-cooling cycles on TCR: 1 – after 25 cycles; 2 – after 50 cycles; 3 – after 75 cycles; 4 – after 100 cycles; 5 – after 125 cycles; 6 – after 150 cycles; 7 – after 175 cycles; 8 – after 200 cycles.

Conclusion

The effect of the operational parameters on Thermal Contact Resistance (TCR) in a copper-aluminum L-type finned tube was experimentally investigated. The investigated operational parameters were: the maximum operational temperature and the number of repeated heating-cooling cycles.

The experimental results showed a TCR increase of 81%, as the average temperature difference between hot inner flow and cooling air increased from 30 °C to 130 °C. In addition, it was found that after the recommended maximum operational temperature (120°C) is reached, the TCR increases faster than before. Finally, after 200 repeated heating-cooling cycles, the TCR presented an increase of 31% with respect to the initial value before the heating-cooling testing. Based on these findings, it is recommended that the air-cooled heat exchangers composed of copper-aluminum L-type finned tubes should operate continuously, avoiding repeated heating-cooling cycles. Furthermore, the operational temperature should be below 120 °C; otherwise, the increment of the TCR could substantially affect the equipment's performance.

The experimental results may be useful, especially the on the TCR values for a core tube external surface temperature between 55 and 155 °C, as a reference for preliminary thermal design of heat exchangers based on copper-aluminum L-type finned tubes.

Acknowledgment

The authors wish to express their thanks to the National Polytechnic Institute of Mexico for their support of this work.

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