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The Effect of Lubricant Concentration,  
Miscibility, and Viscosity on R134a Pool  
Boiling

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# The Effect of Lubricant Concentration, Miscibility, and Viscosity on R134a Pool Boiling

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## ABSTRACT

This paper presents pool boiling heat transfer data for twelve different R134a/lubricant mixtures and pure R134a on a Turbo-BII<sup>TM</sup>-HP<sup>1</sup> surface. The mixtures were designed to examine the effects of lubricant mass fraction, viscosity, and miscibility on the heat transfer performance of R134a. The magnitude of the effect of each parameter on the heat transfer was quantified with a regression analysis. The mechanistic cause of each effect was given based on new theoretical interpretation and/or one from the literature. The model illustrates that large improvements over pure R134a heat transfer can be obtained for R134a/lubricant mixtures with small lubricant mass fraction, high lubricant viscosity, and a large critical solution temperature (CST). The ratio of the heat flux of the R134a/lubricant mixture to that of the pure R134a for fixed wall superheat was given as a function of pure R134a heat flux for all twelve mixtures. The lubricant that had the largest CST with R134a exhibited the greatest heat transfer: 100 %  $\pm$  20 % greater than that of pure R134a. By contrast, the heat transfer of the mixture with the lubricant that had the smallest viscosity and the smallest CST with R134a was 45 %  $\pm$  9 % of that of pure R134a. High-speed films of the pure and mixture pool boiling were taken to observe the effect of the lubricant on the nucleate boiling.

Keywords: alternative refrigerants, boiling, concentration, enhanced heat transfer, miscibility, pool boiling, R134a, refrigerant/lubricant mixtures, surfactant, viscosity, visualization

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<sup>1</sup> Certain trade names and company products are mentioned in the text or identified in an illustration to adequately specify the experimental procedure and equipment used. In no case does such an identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

## INTRODUCTION

The ability to predict the effect of lubricant on the pool boiling heat transfer of refrigerants based on the properties of the lubricant has been elusive for some time. Modeling of refrigerant/lubricant mixture pool boiling has two main obstacles. First, it must be determined what lubricant properties are important and how they influence heat transfer. Second, a mechanistic model that physically represents the way a lubricant interacts with a refrigerant in the determination of heat transfer must be developed. Most of the work in refrigerant/lubricant mixture pool boiling has been done with these goals in mind.

For example, Sauer et al. (1978) believed that lubricant viscosity and surface-tension effects were important in determining the magnitude of the nucleate boiling of refrigerants, but they could not correlate these effects. Hahne and Noworyta (1984) also presumed that the lubricant viscosity should have an effect on pool boiling of refrigerant/lubricant mixtures, but they were unable to include it in their heat transfer correlation.

Another important parameter for pool boiling is the lubricant mass fraction. For instance, the effect of lubricant on the pool boiling performance of a Turbo-BII<sup>TM</sup> tube for R114, R124, and R123 has been investigated by Memory et al. (1993), Memory et al. (1995), and Webb and McQuade (1993), respectively. Although improvements in heat transfer with the addition of lubricant were measured by Memory et al. (1993 and 1995) for finned tubes, only degradations in heat transfer were measured for the refrigerant/lubricant mixtures and the Turbo-BII<sup>TM</sup> tube. In both of the Memory et al. (1993 and 1995) studies, they also found that for lubricant mass fractions greater than 6 %, increases in lubricant concentration led to decreases in heat transfer. Bell et al. (1987) found that this decrease was greater than would be expected based on mole fraction weighting.

Although no studies investigating the effect of lubricant miscibility on heat transfer were found, several works correlate the lubricant effect to the properties of the refrigerant/lubricant mixture. For example, Jabardo and da Silva (1991) developed a model for the pool boiling of R11, R113 and R114 lubricant mixtures by correlating the Rohsenow (1951) surface/liquid parameter to the bubble Stanton number and to the Jakob number for each refrigerant/lubricant mixture. Another study by Chongrungreong and Sauer (1980) developed a correlation for the pool boiling heat transfer of refrigerant/lubricant mixtures based on the refrigerant volume fraction and the mixture liquid Prandtl number.

Many researchers hypothesize that foaming is the main governing heat transfer mechanism for refrigerant/lubricant mixtures. Stephan (1963) was one of the first researchers to connect foaming and refrigerant/lubricant evaporation and to note that an oil-rich layer exists near the tube wall. Memory et al. (1993 and 1995) also attributed the enhancement of refrigerant pool boiling heat transfer with lubricants to lubricant foaming. Other models, such as those by Jensen and Jackman (1984) and Mitrovic (1998), focus on the lubricant-rich layer that exists around the liquid-vapor interface of the bubble.

Yet, Burkhardt and Hahne (1979) believed that the influence of lubricant on pool boiling cannot be completely explained by liquid-vapor surface tension effects or by foaming.

The mechanistic model that is endorsed in this manuscript was developed in a series of studies: Kedzierski (1993) and Kedzierski and Kaul (1993), Kedzierski (1999a), and Kedzierski, (1999b). In these studies, it was speculated that the pool boiling enhancement/degradation mechanism associated with the addition of a lubricant to refrigerant is due to an accumulation of lubricant at the boiling surface. The enhancement mechanism of lubricants is analogous to the action of surfactants in that both enhancements arise from the creation of an excess layer. Kedzierski (1999a) measured a significant enhancement of R123 pool boiling with the addition of 1 % and 2 % hexane by mass to R123. He used the Gibbs adsorption equation (Rosen, 1978) and the Young and Dupre equation (Adamson, 1967) to speculate that the boiling heat transfer enhancement of R123 by the addition of hexane was caused by an accumulation of hydrocarbon at the boiling surface. In essence, the greater concentration of hydrocarbon or “excess layer” at the heat transfer surface caused a reduction of the surface energy between the solid surface and the liquid. The existence of an excess layer at the liquid-solid interface is analogous to the existence of a surfactant-induced excess layer at a liquid-vapor interface. Consequently, hydrocarbons and lubricants are not typical surfactants because they accumulate at the solid-liquid interface rather than at the liquid-vapor interface. However, the reduction in the liquid-solid surface energy results in a similar reduction in bubble departure diameter that occurs with a conventional surfactant. As a consequence of the bubble size reduction, the active site density increases. A heat transfer enhancement exists when a favorable balance between an increase in site density and a reduction in bubble size occurs.

To build upon the above mechanistic model, the influence of lubricant properties on the pool boiling heat transfer must be determined. Toward this end, the boiling behavior of R134a on a Turbo-BII<sup>TM</sup>-HP surface with four different polyolester lubricants (POEs) of three different mass fractions under 4 % was investigated. Table 1 gives the viscosity of the lubricants at 313.15 K: 4.59  $\mu\text{m}^2/\text{s}$ , 21.76  $\mu\text{m}^2/\text{s}$ , 25.34  $\mu\text{m}^2/\text{s}$ , and 197.36  $\mu\text{m}^2/\text{s}$ . Table 1 also gives the three different critical solution temperatures (CSTs) of the R134a/lubricant mixtures that were investigated: 203 K, 237 K and 270 K. The viscosities and CSTs of the lubricants cover the application range for refrigeration and air-conditioning equipment. Low viscosity lubricants are typically used with R134a home appliances. Screw compressors require high viscosity lubricants. Most refrigeration and air-conditioning applications require lubricants that are miscible with the refrigerant. But some applications permit the lubricant to be partially miscible with R134a.

Typically, the lubricant viscosity and its miscibility with the refrigerant are interesting in terms of how they influence the return of the lubricant to the compressor. This study shows that the very properties that favor oil return promote poor pool boiling heat transfer. Namely, a lubricant with a low viscosity and a complete miscibility with the refrigerant may promote lubricant return (Bateman, 1997), but these characteristics are detrimental to heat transfer. Because of lubricant return concerns, Didion (1999) states that a “lubricant crisis” could exist if the new lubricants are less soluble in the new

refrigerants. However, the heat transfer benefit that can be obtained with the high viscosity and partially miscible lubricants may represent an opportunity rather than a crisis where lubricant return is not a problem or where it can be achieved by other means. In this way, manufacturers may be able to choose a lubricant that satisfies the lubricating requirements of the compressor and also enhances the heat transfer of the evaporator.

## APPARATUS

Figure 1 shows a schematic of the apparatus that was used to measure the pool boiling data of this study. Specifically, the apparatus was used to measure the liquid saturation temperature ( $T_s$ ), the average pool-boiling heat flux ( $q''$ ), and the wall temperature ( $T_w$ ) of the test surface at the root of the fin. The three principal components of the apparatus were test chamber, condenser, and reservoir. The internal dimensions of the test chamber were 25.4 mm  $\times$  257 mm  $\times$  1.54 m. The test chamber was charged with approximately 7 kg of R134a from the reservoir, giving a liquid height of approximately 80 mm above the test surface. As shown in Fig. 1, the test section was visible through two opposing, flat 150 mm  $\times$  200 mm quartz windows. A high-speed camera was used to film the boiling at 1000, 3000, and 6000 frames per second (fps). Two 500 W forward lights illuminated the specimens during filming. Films were taken at selected heat fluxes immediately after the measurement of the heat-transfer coefficient to ensure that the heat from the lights did not influence the measurement. The bottom of the test surface was heated with high velocity (2.5 m/s) water flow. The vapor produced by liquid boiling on the test surface was condensed by the brine-cooled, shell-and-tube condenser and returned as liquid to the pool by gravity.

To reduce the errors associated with the liquid saturation temperature measurement, the saturation temperature of the liquid was measured with a 450 mm long 1.6 mm diameter stainless steel sheathed thermocouple. The small diameter provided for a relatively rapid response time. To minimize conduction errors, nearly the entire length of the thermocouple was in contact with either the test refrigerant vapor or liquid. The tip of the thermocouple was placed approximately 2 mm above and 150 mm to one side of the top of the test surface. This placement ensured that approximately 80 mm of the probe length was in relatively well-mixed liquid near the two-phase fluid above the test surface. To provide for a saturated liquid pool state, the mass of liquid in the pool was large compared to the mass of liquid condensed. At the highest heat flux, nearly one hour was required to evaporate and condense the entire test chamber charge. The lack of a temperature difference between the probe and the well-insulated, low emissivity, 38 mm aluminum test chamber walls essentially eliminated temperature errors due to radiation to the probe.

## TEST SURFACE

Figure 2 shows the oxygen-free high-conductivity (OFHC) copper Turbo-BII™-HP test plate and thermocouple coordinate system used in this study. Commercially, the Turbo-BII™-HP surface is formed by a rolling process on a smooth copper tube. The test plate was machined out of a single piece of OFHC copper by electric discharge machining (EDM). The Turbo-BII™-HP surface in this study was flattened from a 25 mm OD annealed copper tube and soldered onto the top of the test plate. Figure 3 shows a photograph of the fin surface. The Turbo-BII™-HP surface has approximately 2250 fins per meter (fpm) oriented along the short axis of the plate. A canopy of copper diamonds merge to create 0.1 mm wide (approximately) slit openings to the root of the fin ranging from approximately 0.1 mm to 0.3 mm in length. The overall height and root-width of a fin are 0.8 mm and 0.2 mm, respectively.

## MEASUREMENTS AND UNCERTAINTIES

The standard uncertainty ( $u_i$ ) is the positive square root of the estimated variance  $u_i^2$ . The individual standard uncertainties are combined to obtain the combined standard uncertainty ( $u_c$ ) by the law of propagation of uncertainty. The  $u_c$  becomes an expanded uncertainty ( $U$ ) when it is multiplied by a coverage factor to correspond to a particular confidence interval. All of the measurement uncertainties reported in this document are expanded uncertainties ( $U$ ) for a 95 % confidence interval except where specified otherwise.

The thermocouples were calibrated against a standard in the NIST Temperature Group to a residual standard deviation of 0.005 K. Considering the fluctuations in the saturation temperature during the test and the standard uncertainties in the calibration, the  $u_c$  of the average saturation temperature was no greater than 0.04 K. A thermocouple drift of within 0.1 K was determined by recalibrating the thermocouples a year after the tests were completed. Consequently, the  $u_c$  of the temperature measurements was less than 0.1 K.

Figure 2 shows the coordinate system for the 20 wells where individual thermocouples were force-fitted into the side of the test plate. The wells were 16 mm deep to reduce conduction errors. Using a method given by Eckert and Goldstein (1976), errors due to heat conduction along the thermocouple leads were estimated to be well below 0.01 mK. The origin of the coordinate system was centered on the surface with respect to the y-direction at the plate surface-solder layer interface. Centering the origin in the y-direction improved the accuracy of the wall heat flux and temperature calculations by reducing the number of fitted constants involved in these calculations. The x-coordinate measures the distance normal to the heat transfer surface. The y-coordinate measures the distance perpendicular to the x-coordinate. The thermocouples were arranged in four sets of five aligned in the x-direction. Following a procedure given by Kedzierski and Worthington (1993), the size and arrangement of the thermocouple wells were designed to minimize the errors in the wall temperature and temperature gradient measurement.

The heat flux and the wall temperature were obtained by regressing the measured temperature distribution of the copper plate to the governing two-dimensional conduction equation (Laplace equation). In other words, rather than using the boundary conditions to



solve for the interior temperatures, the interior temperatures were used to solve for the boundary conditions following a backward stepwise procedure given in Kedzierski (1995).

The backward stepwise regression was used to determine the best model or the significant terms of the solution to the Laplace equation in rectangular coordinates for each data point. Most infinite series solutions should converge within nine terms. The backward stepwise method began by regressing the first nine terms of the infinite series solution to the twenty measured plate temperatures:

$$T = C_0 + C_1x + C_2y + C_3(x^2 - y^2) + 2C_4xy + C_5x(x^2 - 3y^2) + C_6y(3x^2 - y^2) + C_7(x^4 - 6x^2y^2 + y^4) + 4C_8(x^3y - xy^3) \quad 1$$

The above “full” model was reduced to its significant terms by removing terms with t-values less than two while maintaining the original residual standard deviation of the full model. Terms were removed one at a time. Regression of the 20 temperatures was done after each term with the smallest t-value was removed. Table 2 provides an overview of the various two-dimensional conduction models that were used to reduce the measured temperatures to heat fluxes and wall temperatures. The top three most frequently occurring models are given with the corresponding percentage of appearance.

Fourier's law and the fitted constants ( $C_0, C_1, \dots, C_n$ ) were used to calculate the average heat flux ( $q''$ ) normal to and evaluated at the heat transfer surface, e.g.:

$$q'' = \left( \frac{1}{L_y} \int_{-\frac{L_y}{2}}^{\frac{L_y}{2}} k \frac{\partial T}{\partial x} dy \right)_{x=0} = \bar{k}C_1 \quad 2$$

where  $\bar{k}$  is the average thermal conductivity along the surface of the plate, and  $L_y$  is the length of the heat transfer surface as shown in Fig. 2.

The average plate-solder layer interface temperature ( $T_i$ ) was calculated by integrating the local temperature of the heat surface just below the solder layer that attached the Turbo-BII™-HP tube to the test surface:

$$T_i = \left( \frac{1}{L_y} \int_{-\frac{L_y}{2}}^{\frac{L_y}{2}} T dy \right)_{x=0} \quad 3$$

For most models, the above equation reduces to:

$$T_i = C_0 \quad 4$$

A linear conduction model was used to calculate the heat transfer across the solder layer and the average wall temperature at the root of the fin ( $T_w$ ). Appendix A discusses the procedure that was used to extrapolate the wall temperature of the surface while accounting for the solder layer and the thickness of the tube at the fin root. Figure 4 shows the expanded uncertainty in the temperature at the root of the fin ( $U_{T_w}$ ) as a function of the heat flux for the thirteen test fluids on the Turbo-BII<sup>TM</sup>-HP test surface. The correction for the solder layer adds approximately 0.004 K to the expanded uncertainty of  $T_w$ . The expanded uncertainty of  $T_w$  was calculated from the regression of the solution to Laplace's equation. The mean uncertainties in the wall temperature for the five fluids range from approximately 0.03 K at 5 kW/m<sup>2</sup> to 0.09 K at 160 kW/m<sup>2</sup>. The average random error in the wall temperature difference --  $\Delta T_s = T_v - T_w$  -- for all of the fluids was within 0.07 K for heat fluxes less than 80 kW/m<sup>2</sup>.

Figure 5 shows the relative (percent) uncertainty of the heat flux ( $U_{q''}$ ) as a function of the heat flux. Siu et al. (1976) estimated the expanded uncertainty in the thermal conductivity of OFHC copper to be about 2 % to 3 % by comparing round-robin experiments. Considering this, the relative expanded uncertainty in  $q''$  was greatest at the lowest heat fluxes, being between 3 % and 10 % for heat fluxes less than 10 kW/m<sup>2</sup>. In general, the  $E_{q''}$  appears to remain between 2.8 % and 4 % for heat fluxes greater than 30 kW/m<sup>2</sup>.

The uncertainties shown in Figs. 4 and 5 are "within-run uncertainties." These do not include the uncertainties due to "between-run uncertainties" or differences observed between tests taken on different days. The "within-run uncertainties" include only the random effects and uncertainties evident from one particular test. All other uncertainties reported here are "between-run uncertainties" which include all random effects such as surface past history or seeding. "Within-run uncertainties" are given only in Figs. 4 and 5.

The test rig and the test surface were thoroughly cleaned after each lubricant mixture was tested. A checkout test followed, which confirmed that the rig was clean by reproducing the pure R134a data. If the checkout test did not reproduce the pure R134a results within 3 %, the rig and surface were cleaned again, and the test was repeated.

## **POOL-BOILING MEASUREMENTS**

The heat flux was varied from approximately 10 kW/m<sup>2</sup> to 160 kW/m<sup>2</sup>. This test range includes the operating conditions of R134a chillers equipped with enhanced tubes. All evaporation tests were taken at a saturation temperature of 277.6 K. The data were consecutively recorded starting at approximately 160 kW/m<sup>2</sup> and then descending to 10 kW/m<sup>2</sup>. The descending heat flux procedure minimized the possibility of any hysteresis effects on the data, which would have made the data sensitive to the initial operating conditions. Table 3 presents the measured heat flux and wall superheat for all of the data of this study. Table 4 provides the number of test days and total number of measured test points for each fluid. On average, nine days of data or approximately 165 data points were taken for each fluid.

The mixtures were prepared by first charging approximately 90 % of a known mass of R134a into an evacuated reservoir (see Fig. 1). The liquid was injected into a drop tube that nearly touched the bottom of the reservoir. For the near 0.5 % composition, the lubricant was first injected with a syringe through the drop tube. Next, the drop tube was flushed with the remaining R134a charge. For the remaining two lubricant compositions, additional lubricant was injected with the aid of R134a as a propellant. The flushing of R134a propellant vapor through the drop tube also assisted in sample mixing. The mass fraction was determined from the masses of the charged components. Three nominal lubricant mass fractions were investigated: 0.5 %, 1 %, and 2 %. The expanded uncertainty of the mass fraction measurement for plus or minus three standard deviations was approximately 0.02 %, e.g., the range of a 0.5 % composition was between 0.48 % and 0.52 %. The DE601, DE590, and DE599 mixtures with R134a have a greater uncertainty of approximately  $\pm 0.06$  % for the two highest concentrations. The heat-transfer test chamber was charged with the test fluid from the reservoir before each day of testing.

Figures 6 through 18 are plots of the measured heat flux ( $q''$ ) versus the measured wall superheat ( $T_w - T_s$ ). Symbols represent the data points. The solid line is a best-fit regression or estimated mean of the data. A single cubic fit was used to regress the wall superheat against the heat flux for the entire heat flux range. Table 5 gives the constants for the cubic regression for each test fluid. Figure 19 plots the cubic fits for all of the test fluids on logarithmic scales. The residual standard deviation of the regressions - representing the proximity of the data to the mean - are given in Table 6. On average, the residual standard deviation of the pure R134a and the (99.5/0.5) mixture data about the mean was approximately 0.1 K. Figure 20 shows that the residual standard deviation of the cubic fit increases approximately linearly with respect to lubricant mass fraction for each lubricant except DE589. The dashed lines to either side of the mean represent the lower and upper 95 % simultaneous (multiple-use) confidence intervals for the mean. The expanded uncertainty of the estimated mean wall superheat for pure R134a and the (99.5/0.5) mixtures, the (99/1) mixtures and the (98/2) mixtures was on average 0.05 K, 0.1 K, and 0.16 K, respectively. Table 7 provides the average mean wall temperature expanded uncertainty for all of the fluids.

Because of the random trends of the cubic fit residual plots, the increase in the lack of reproducibility with increasing concentration shown in Fig. 20 is believed to be caused by a true physical phenomenon. Apparently for some R134a/lubricant mixtures, larger bulk lubricant concentrations can lead to greater variability in the data from day-to-day, which leads to a spreading of the data. A possible explanation for the sensitivity of the data is that higher bulk concentrations exhibit a greater day-to-day variation in the bubble size and site density. The variation in the bubble parameters is likely linked directly to the between-run variation in the concentration of the lubricant excess layer at the surface. This suggests that the variation in the lubricant concentration at the surface may be greater for higher bulk concentrations and result in a greater variation in the heat transfer. Considering the absence of site density and bubble size data for the entire heat flux range and a model to relate these bubble parameters to the heat flux, a simple cubic fit provided an unbiased means for comparison of all the data.

Figure 6 presents the boiling curve for pure R134a at  $T_s = 277.6$  K on the Turbo-BII<sup>TM</sup>-HP surface. The R134a pool boiling data of Chen and Tuzla (1996) on a 19 mm OD Turbo-BII<sup>TM</sup>-HP tube at  $T_s = 277.6$  K is also given on this figure. The Chen and Tuzla (1996) wall superheat is anywhere from 0.2 K to 0.5 K greater than the mean wall superheat of the NIST data for a given heat flux. Differences in heat transfer performance between the flat plate and the round tube arise primarily from differences in the bulk fluid motion and the conduction experienced by the two surfaces. Bulk fluid motion, including the sliding bubble effect (Cornwell and Einarsson, 1989), should cause the tube performance to be greater than that of the flat plate. Conduction effects should be small for the copper tube and plate. As a consequence, the proximity of the two data sets suggests that either: (1) there are compensating effects between, for example, the heat transfer enhancement by bulk fluid motion and measurement errors for the tube, or (2) the bulk fluid motion has only a minimal affect on the heat transfer performance of the enhanced tube. Possibly, the fin canopies of the Turbo-BII<sup>TM</sup>-HP shelter the nucleate boiling from the bulk fluid motion causing the boiling to be independent of the fluid motion. In any case, it appears that the flat test surface provides a fair representation of the performance of a tube but with the advantage of significantly smaller measurement uncertainties.

### ENHANCEMENT TRENDS

Figures 21 through 24 summarize the effect of adding lubricant to R134a on the R134a heat flux. Each figure plots the ratio of the mixture heat flux ( $q''_m$ ) to the pure R134a heat flux ( $q''_p$ ) versus the pure R134a heat flux at the same wall superheat. The 95 % confidence interval for the heat flux ratio is depicted as a shaded region in the figures.

In general, a boiling enhancement occurs for the 0.5 % lubricant mass fraction for all of the refrigerant/lubricant mixtures that were tested. For the most part, the mixture heat flux diminishes with increasing lubricant mass fraction. The rate of degradation with increasing mass fraction is less severe for mixtures with the DE589 lubricant. Also, no enhancement occurs for the 2 % lubricant concentration for any of the mixtures. In addition, the heat transfer for all of the R134a/lubricant mixtures decreases with respect to increasing heat flux for heat fluxes greater than 60 kW/m<sup>2</sup>. Although the heat flux ratio is shown to increase with heat flux in some regions, the corresponding uncertainties in the heat flux ratio are too large to confirm that trend.

Figure 21 shows the heat flux ratio for three mixtures of R134a and the DE599 lubricant. The viscosity of the DE599 lubricant is the smallest of the four lubricants (4.6 μm<sup>2</sup>/s at 313 K), and it is miscible with R134a at the test temperature. For the most part, the R134a boiling was not enhanced by the addition of DE599. The sole improvement in the heat transfer was an average 3 % increase in the heat flux between approximately 30 kW/m<sup>2</sup> and 80 kW/m<sup>2</sup> for the (99.5/0.5) mixture. In addition, the R134a/DE599 (97.7/2.3) mixture exhibited the greatest degradation in heat transfer; the heat flux ratio was approximately 0.45 ± 0.09 for the entire heat flux range. The greatest heat flux ratio exhibited by the R134a/DE599 (98.9/1.1) mixture was 0.91 ± 0.03 at 58.2 kW/m<sup>2</sup>.

Figure 22 shows the heat flux ratio for three mixtures of R134a and the DE601 lubricant. The viscosity of the DE601 lubricant is the greatest of the four lubricants (197.36 μm<sup>2</sup>/s at

313 K), and it has the same CST as the DE599 lubricant with R134a (203 K). Two mixtures of DE601 with R134a (99.5/0.5 and 98.7/1.3) exhibit a substantial enhancement within the operating range of R134a chillers. Specifically, a 16 % and a 9 % average enhancement of the pure R134a heat flux was obtained between approximately 14 kW/m<sup>2</sup> and 81 kW/m<sup>2</sup>. The two greatest heat flux ratios were  $1.47 \pm 0.06$  and  $1.37 \pm 0.1$ , which were obtained at approximately 14 kW/m<sup>2</sup> for the (99.5/0.5), and the (98.7/1.3) mixture, respectively. The (96.7/3.3) mixture exhibits a heat transfer degradation with respect to the heat transfer of pure R134a for all heat fluxes. Performance loss due to a given increase in mass fraction was more severe when the lubricant mass fraction was increased from 1.3 % to 3.3 % than it was when the increase was from 0.5 % to 1.3 %.

Figure 23 shows the heat flux ratio for three mixtures of R134a and the DE590 lubricant. The viscosity of the DE590 lubricant is between that of the DE601 and the DE599 lubricants ( $25.34 \mu\text{m}^2/\text{s}$  at 313 K), and it has a slightly higher CST (237 K) with R134a than these lubricants. The R134a/DE590 (99.5/0.5) mixture exhibits a maximum heat flux increase over that of pure R134a of  $37 \% \pm 14 \%$  at approximately 9 kW/m<sup>2</sup>. The average heat flux ratio for the R134a/DE590 (99.5/0.5) mixture is 1.18 over the heat flux range of interest to chillers - from approximately 11 kW/m<sup>2</sup> to 81 kW/m<sup>2</sup>. By contrast, the heat flux ratios of the R134a/DE590 (98.8/1.2) and the R134a/DE590 (97.3/2.7) mixtures are significantly less than that of the (99.5/0.5) mixture being  $0.9 \pm 0.03$  and  $0.6 \pm 0.5$  at 110 kW/m<sup>2</sup>, respectively. Notice that because the confidence intervals for both the R134a/DE590 (98.8/1.2) and the R134a/DE590 (97.3/2.7) mixtures include  $q''_m/q''_p = 1$  at low heat flux, the relative performance of these mixtures with respect to pure R134a is indeterminate in this region.

Figure 24 shows the heat flux ratio for three mixtures of R134a and the DE589 lubricant. The viscosity of the DE589 lubricant is nearly the same as that of the DE590 lubricant ( $21.76 \mu\text{m}^2/\text{s}$  at 313 K), and it has the highest CST (270 K) with R134a of all the lubricants. Mixtures of R134a with DE589 exhibit the largest enhancements with respect to R134a and are not as sensitive to lubricant concentration as the other lubricants investigated. In fact, the 0.5 % and 1 % concentrations with DE589 have nearly identical performances for pure heat fluxes greater than 50 kW/m<sup>2</sup>. The maximum heat flux ratio for R134a/DE589 (99.5/0.5) is  $2.0 \pm 0.2$  at approximately 5 kW/m<sup>2</sup>. The maximum heat flux ratio for R134a/DE589 (99/1) is  $1.18 \pm 0.02$  at approximately 40 kW/m<sup>2</sup>. The heat flux ratio for the 0.5 % and 1 % DE589 mixtures, averaged over approximately 10 kW/m<sup>2</sup> and 81 kW/m<sup>2</sup>, is 1.24 and 1.13, respectively. The 2 % DE589 mixture with R134a exhibits a boiling performance approximately equal to that of pure R134a.

### Regression Analysis

The heat flux ratios given in Figs. 21 through 24 provide the heat transfer performance of the R134a/lubricant mixtures relative to that of pure R134a for each of the four R134a/lubricant sets. However, the effects of lubricant viscosity, CST ( $T_c$ ), and lubricant mass fraction on the mixture heat transfer are not easily isolated nor understood with heat flux ratio plots alone. To remedy this, a regression analysis of the average heat flux ratios for each mixture versus the three salient factors and their coupling is presented. Table 8 provides the average heat flux ratio versus the three regression factors for each

R134a/lubricant mixture. The heat flux ratios were averaged from approximately 10 kW/m<sup>2</sup> to 80 kW/m<sup>2</sup>. The regression factors were: (1) the lubricant mass fraction ( $x_m$ ), (2) the difference between the liquid viscosity of the lubricant and that of the refrigerant normalized by the refrigerant viscosity  $(\nu_L - \nu_r)/\nu_r$  all evaluated at 313 K, and (3) the difference between the saturated fluid temperature and the CST of the R134a/lubricant mixture normalized by the fluid temperature  $(T_s - T_c)/T_s$ . The normalized viscosity difference was evaluated at 313 K due to the lack of lubricant viscosity data at  $T_s$ . However, the use of  $(\nu_L - \nu_r)/\nu_r$  at 313 K is sufficient to illustrate the relative effects of viscosity.

Figure 25 shows a plot of the average heat flux ratio versus lubricant mass fraction for the four lubricant mixtures of this study. Clearly, the pool boiling performance decreases with respect to increasing lubricant mass fraction for each R134a/lubricant mixture. Sato et al. (1999) have shown a similar pool boiling performance decrease with respect to increasing lubricant mass fraction for R134a/PAG lubricant mixtures. Because of the large variability of the data shown in Fig. 25, the lubricant mass fraction evidently does not capture the entire dependence of the heat flux ratio.

At this point, a regression analysis to determine the importance of each of the selected R134a/lubricant properties for pool boiling was done. A total of seven factors - the three salient factors listed above plus four interaction terms- were examined for their influence on the heat flux ratio. As a result, the following model of the average heat flux ratio was fitted to within  $\pm 0.1$  for 95 % confidence:

$$\frac{\overline{q_m}}{q_p} = 1.25 - x_m \left\{ 91.9 - \left( \frac{\nu_L - \nu_r}{\nu_r} \right) \left[ 0.529 - 1.92 \left( \frac{T_s - T_c}{T_s} \right) \right] - 211 \left( \frac{T_s - T_c}{T_s} \right) \right\} \quad 5$$

Figure 26 plots the measured heat flux ratio versus that predicted by Eq. 5. The figure illustrates that including the lubricant viscosity and the miscibility effects have nearly collapsed the data of Fig. 25 onto a single line. Equation 5 shows that a small lubricant mass fraction, a small  $(T_s - T_c)/T_s$ , and a large lubricant viscosity all tend to benefit R134a/lubricant pool boiling heat transfer. The lubricant mass fraction is the most influential of the governing parameters. As compared to  $x_m$ , the lubricant viscosity and the  $(T_s - T_c)/T_s$  are less important, but they are still significant for determining the magnitude of the average heat flux ratio. Notice that the lubricant viscosity parameter is coupled to the  $(T_s - T_c)/T_s$  parameter. Here the  $(T_s - T_c)/T_s$  parameter reduces the effect of viscosity on the heat transfer. For example, if a lubricant has a large viscosity that will benefit heat transfer, but if it also has a test temperature that is far from the CST, then the viscosity enhancement effect will be somewhat lessened by the large  $(T_s - T_c)/T_s$ .

There are a couple of caveats that should be given with Eq. 5. First, the quantity within the outermost brackets that multiplies  $x_m$  must be greater than zero to provide for a decreasing enhancement with respect to increasing lubricant mass fraction. Otherwise, heat flux ratios of 60 at a lubricant mass fraction of 10 % can be obtained for the highest lubricant viscosity and the lowest CST. For these inputs, the model predicts that the heat

flux ratio increases with increasing mass fraction for mass fractions greater than 5 %, which is inconsistent with current experience. However, if the viscosity and CST inputs to the model were limited such that the model produced only decreasing heat flux ratios with respect to mass fraction, then the highest possible enhancement would be approximately 25 %. A limit on the enhancement also does not make physical sense. Finally, the model predicts an enhancement ratio of 1.25 rather than 1.00 for pure R134a. Consequently, the above model should only be used to illustrate the trends of the current data set for positive values of the  $x_m$  multiplier.

### MECHANISTIC INTERPRETATION

The above regression analysis has shown that the viscosity, the CST, and the lubricant mass fraction are important factors for R134a pool boiling. The analysis also shows that the influences of viscosity and CST are coupled. The role that the lubricant mass fraction, the viscosity, and the miscibility have on R134a pool boiling can be understood by analyzing how these parameters interact with the lubricant excess layer. The lubricant excess layer exists as a region of liquid near a heated wall with a lubricant concentration that is greater than that of the bulk fluid. In the following, mechanistic interpretations are offered to explain how each of the influential factors affect R134a pool boiling.

Larger lubricant mass fractions promote smaller bubble departure diameters, which, in turn, can lead to poorer heat transfer (Kedzierski, 1992 and Kedzierski and Kaul, 1993). As outlined by Kedzierski (1999b), the excess layer causes a reduction in the liquid-solid surface energy ( $\sigma_{ls}$ ) that results in a simultaneous reduction in the bubble departure diameter and an increase in the site density. This was illustrated with the Gibbs adsorption equation for a dilute solution (Rosen, 1978), which shows that a greater surface energy reduction results for increases in the surface excess concentration ( $\Gamma$ ) and/or increases in the bulk lubricant concentration ( $C$ ):

$$d\sigma = -RT_e \Gamma d \ln c \quad 6$$

where  $R$  is the universal gas constant, and  $T_e$  is the temperature of the interface. A heat transfer enhancement existed when the increase in site density more than compensates for the reduction in bubble size. However, as the lubricant mass fraction increases, the bubble size decreases while the site density increases. The Mikic and Rohsenow (1969) pool boiling model shows that the heat flux is directly proportional to the product of the site density and the square of the bubble departure diameter. Consequently, the influence of the bubble size on the heat transfer is greater than that of the site density. As a result, the pool boiling heat transfer eventually degrades with increased lubricant mass fraction.

Even for small bulk lubricant mass fractions, a large lubricant viscosity benefits pool boiling by promoting a thick thermal boundary layer. The existence of the excess layer accentuates the influence of the lubricant properties on the heat transfer because pool boiling is controlled in large part by the fluid properties at the heated wall. Because of the excess layer, the viscosity of the liquid near the wall can be significantly greater than what it would have been for the bulk mixture. An estimate of the relative pool boiling thermal boundary layer thickness for two lubricants (subscripts 1 and 2) was derived

from the model of Bosnjakovic (1930) while assuming that the bubble frequency was not influenced by lubricant properties:

$$\frac{\delta_1}{\delta_2} = \sqrt{\frac{v_1 Pr_2}{v_2 Pr_1}} \quad 7$$

In general, the Prandtl number ( $Pr$ ) does not differ much from lubricant to lubricant despite a large variation in viscosity. Consequently, Eq. 7 shows that the thermal boundary layer is a strong function of viscosity providing a thicker thermal boundary layer for larger viscosities. A thicker thermal boundary, in turn, provides for a larger active site density (Hsu, 1962), which improves the pool boiling heat transfer.

The fact that viscosity and CST are coupled is analogous with the prediction of viscosity relative to the proximity of the CST. Laesecke (1999) has observed that the deviation of the measured viscosity from an ideal mixing rule for R32/propane increases as the CST is approached. Laesecke (1999) believes that the interaction between the polar R32 and the nonpolar propane is responsible for the nonideal behavior of the viscosity near the CST. Because the R134a/lubricant mixture is a polar/nonpolar mixture, a similar nonideal behavior of the viscosity near the CST should be expected. Although this does not explain the interdependence of the lubricant viscosity and the CST, it does establish precedence for the interaction that is quantified in Eq. 5.

The proximity of the bulk fluid temperature to the CST of the mixture benefits pool boiling heat transfer by the formation of additional excess liquid films that draw superheated liquid onto the bubble sides. Mitrovic (1998) describes how a lubricant-rich film exists around the liquid-vapor interface of the refrigerant bubble. According to Jensen and Jackman (1984), the lubricant-rich layer is formed by preferential evaporation of the refrigerant at the bubble's liquid-vapor interface. However, it is possible that the bubble may also lift a portion of the lubricant excess layer from the heated wall. In any case, given that an excess lubricant layer surrounds the bubble, Fig. 27 shows how a small difference between the bulk fluid temperature and the CST can dramatically affect the pool boiling heat transfer.



Figure 27 shows a theoretical critical solution diagram for a refrigerant/lubricant mixture and a bubble on a heated wall. The critical solution diagram gives the temperature and the compositions for which the lubricant and refrigerant are miscible. Above the dome, the lubricant and refrigerant are completely miscible for all compositions. Within the dome, two soluble solutions of refrigerant and lubricant exist at different compositions. The closed circle on the critical solution diagram represents the state of the bulk liquid mixture that is close to, but greater than, the CST. The arrow shows how the state of the liquid in the immediate vicinity of the bubble transitions to under the dome by a combination of composition shifting and evaporation at the liquid vapor interface. Once this happens, two thin layers of different refrigerant/lubricant soluble solutions rest on the liquid-vapor interface of the bubble. Of course, only a partial separation is likely because of the short time available before the bubble temperature equilibrates with the bulk liquid. It is also likely that these films are actually liquid droplets that cover regions of the bubble but act like films due to the relative size of the bubble and the droplet. Droplets could also lie adjacent to rather than on top of one another. In any case, the interfaces of the two liquid films are drawn in Fig. 27 to have large curvature gradients. The curvature gradients induce film pressure gradients that transport superheated liquid to the sides of the bubble. The additional bubble superheat is the cause of the pool boiling heat transfer enhancement.

### **VISUAL OBSERVATIONS**

The visual observations from the high-speed films showed that both the type of lubricant and the lubricant mass fraction had a marked effect on bubble formation. From past experience with visual observations, it was believed that pure refrigerant bubbles reflected light readily; whereas, bubbles with lubricant appeared to be dull. In general, the refrigerant/lubricant combination that performed best was where the bubbles remained reflective for low and high lubricant concentrations. Heat transfer degradations with lubricants appeared to be associated with micro-size bubbles and/or a fog of bubbles. For example, the intermediate heat transfer R134a/DE590 mixture bubbles appeared clear or reflective at 0.5 % mass fraction, and then they developed what appeared to be lubricant caps at 1 % mass fraction. Then, finally, they developed into a fog of micro-bubbles at 2 % lubricant mass fraction. Compare this to the high heat transfer bubbles for the R134a/DE590 mixture where lubricant caps did not appear on the bubbles until the 2 % lubricant mass fraction. The low heat transfer bubbles of the R134a/DE599 mixture were misty for all lubricant mass fractions. In summary, R134a/lubricant mixtures that appeared to have less lubricant on the bubbles had superior pool boiling heat transfer performance.

### **CONCLUSIONS**

The pool boiling heat transfer of twelve R134a/lubricant mixtures were compared to that of pure R134a on a Turbo-BII<sup>TM</sup>-HP surface. The mixtures were chosen to examine the effects of lubricant mass fraction, viscosity, and miscibility on heat transfer performance. The range of the lubricant viscosity that was investigated was from 22  $\mu\text{m}^2/\text{s}$  to 197  $\mu\text{m}^2/\text{s}$ . The critical solution temperature (CST) of the R134a/lubricant mixtures ranged from 203 K to 270 K. The lubricant mass fraction of the mixtures ranged from 0.5 to 3.3.

The magnitude of the effect of each parameter on the heat transfer data was quantified with a regression analysis. The mechanistic cause of each effect was given based on new

theoretical interpretation and/or that from the literature. For example, the literature shows that the larger lubricant mass fractions promote smaller bubble departure diameters, which, in turn, leads to poorer heat transfer. New speculation suggests that the proximity of the bulk fluid temperature to the CST of the mixture benefits pool boiling heat transfer by the formation of additional excess liquid films that draw superheated liquid onto the bubble sides. In addition, even for small bulk lubricant mass fractions, a large lubricant viscosity benefits pool boiling by promoting a thick thermal boundary layer. To summarize, the model illustrates that larger heat transfer enhancements can be obtained for small lubricant mass fraction, high lubricant viscosity, and a small difference between the refrigerant saturation temperature and the critical solution temperature of the lubricant.

The ratio of the heat flux of the R134a/lubricant mixture to that of the pure R134a for fixed wall superheat was given as a function of pure R134a heat flux for all twelve mixtures. The greatest heat flux ratio was obtained for the mixture with the lubricant that had the largest CST. For example, the pool boiling performance of R134a was enhanced as much as  $(100 \% \pm 20 \%)$  by adding 0.5 % mass lubricant DE589. Overall, the R134a/DE589 (99.5/0.5) mixture exhibited a 24 % greater heat transfer than pure R134a from approximately  $10 \text{ kW/m}^2$  to  $80 \text{ kW/m}^2$ . The smallest heat flux ratio ( $0.45 \pm 0.09$ ) was obtained for the mixture with the lubricant that had the smallest viscosity and the smallest CST with R134a.

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## NOMENCLATURE

### English Symbols

|                  |   |
|------------------|---|
| $A$              | surface area ( $\text{m}^2$ )                               |
| $c$              | molar concentration of the solute                           |
| $C$              | regression constant (Eq. 1)                                 |
| $k$              | thermal conductivity ( $\text{W}/\text{m}^2\text{K}$ )      |
| $L_y$            | length of test surface in y-direction (m)                   |
| $Pr$             | liquid Prandtl number                                       |
| $q''$            | average wall heat flux ( $\text{W}/\text{m}^2$ )            |
| $R$              | universal gas constant ( $8.314 \text{ J}/\text{K mol}$ )   |
| $R_{\Delta T_w}$ | residual standard deviation of superheat from cubic fit (K) |
| $t$              | thickness (m)   |
| $t_{rt}$         | thickness of the tube wall at the fin root (m)              |
| $T$              | temperature (K)   |
| $T_i$            | plate-solder interface temperature (K)                      |
| $T_w$            | temperature of surface at root of fin (K)                   |
| $U$              | expanded uncertainty for 95 % confidence                    |
| $x$              | test surface coordinate, Fig. 2 (m)                         |
| $X$              | model term (Table 2)  |
| $x_m$            | lubricant mass fraction                                     |
| $y$              | test surface coordinate, Fig. 2 (m)                         |

### Greek Symbols

|              |  |
|--------------|--|
| $\Gamma$     | surface excess concentration of solute       |
| $\delta$     | thermal boundary layer thickness (m)         |
| $\sigma$     | surface tension ( $\text{kg}/\text{m s}^2$ ) |
| $\Delta T_s$ | wall superheat: $T_w - T_s$ , (K)            |
| $\nu$        | viscosity ( $\text{m}^2/\text{s}$ )          |

### Subscripts

|      |   |
|------|---|
| $c$  | lubricant critical solution temperature |
| $cu$ | copper                                  |
| $e$  | excess layer interface                  |
| $L$  | lubricant                               |
| $ls$ | liquid-solid interface                  |
| $m$  | mixture                                 |
| $p$  | pure R134a                              |
| $r$  | refrigerant                             |
| $s$  | saturated liquid or vapor state, solder |
| $t$  | copper tube                             |

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## APPENDIX A

This appendix outlines the procedure that was used to extrapolate the wall temperature of the Turbo-BII™-HP surface. The boiling surface on the Turbo-BII™-HP plate originated as a round tube. The tube was annealed, flattened and soldered onto the top of the plate. The average temperature of the plate-solder interface ( $T_i$ ) was calculated from the regression of the two-dimensional conduction equation as described in the body of this paper. Because the solder layer was thin, a one-dimensional conduction model was used to extrapolate the temperature drop across it.

The solder was 6 % silver and 94 % tin by mass. The thermal conductivity of the solder was fitted to a modified form of the Smith-Palmer equation (Smith and Palmer, 1935) as:

$$k_s = \left( \frac{57.858 \frac{W}{mK}}{T - 38.65K} \right) T + 7.5 \frac{W}{mK} \quad 8$$

where  $T$  is the temperature of the solder layer in Kelvin. The Smith-Palmer equation was modified by replacing the electrical conductivity with a linear relationship with temperature.

The flattened Turbo-BII™-HP tube was phosphorus-deoxidized copper (C12200). The thermal conductivity of the copper ( $k_t$ ) was fitted to:

$$k_t = \left( \frac{422.46 \frac{W}{mK}}{T + 63.33K} \right) T - 37.79 \frac{W}{mK} \quad 9$$

where  $T$  is the temperature of the copper in Kelvin. The average thickness of the solder layer ( $t_s$ ) and the average distance between the copper-solder layer interface and the root of the fin ( $t_{rt}$ ) were measured with an optical-video coordinate-measurement instrument (OVCM). The OVCM instrument had a resolution of 0.005 mm.

The average wall temperature at the root of the fin for the Turbo-BII™-HP plate was calculated from:

$$T_w = T_i - q'' \left( \frac{t_{rt}}{k_t} + \frac{t_s}{k_s} \right) \quad 10$$

The expanded uncertainty of  $T_w$  was calculated considering the uncertainty of each parameter of Eq. 10. The expanded uncertainty of the thickness measurements as calculated from the standard uncertainty of the thickness measurement were estimated to be 0.02 mm. Capillary forces during the soldering process should provide for a uniform solder thickness. The thermal conductivities of the copper and the solder were assumed to be known to within 5 %. For these conditions, the temperature correction for the solder layer contributes 0.01 K, 0.005 K and 0.005 K to the expanded uncertainty of the average wall temperature for 160 kW/m<sup>2</sup>, 80 kW/m<sup>2</sup>, and 20 kW/m<sup>2</sup>, respectively. This additional uncertainty has been included in the combined expanded uncertainty that is shown in Fig. 4 for the Turbo-BII™-HP surface.

Table 1 Properties of Test Lubricants (Corr, 1995)

| Lubricant | Viscosity at 313.15 K<br>( $\mu\text{m}^2/\text{s}$ ) | Critical<br>solution<br>temperature (K) | Miscible<br>in R134a (?) |
|-----------|---|---|--------------------------|
| DE589     | 21.76   | 270.15                                  | partially                |
| DE599     | 4.59  | 203.15                                  | yes                      |
| DE590     | 25.34   | 237.15                                  | yes                      |
| DE601     | 197.36  | 203.15                                  | yes                      |



Table 2 Conduction model choice

| $X_0 = \text{constant (all models)}$ $X_1 = x$ $X_2 = y$<br>$X_3 = xy$ $X_4 = x^2 - y^2$ $X_5 = y(3x^2 - y^2)$ $X_6 = x(3y^2 - x^2)$<br>$X_7 = x^4 + y^4 - 6(x^2)y^2$ $X_8 = yx^3 - xy^3$ |  |
|---|--|
| Fluid   | $q''$  |
| R134a/DE589(99.5/0.5)   | $X_1, X_3$ (87 of 158) 55 %<br>$X_1, X_2$ (55 of 158) 35 %<br>$X_1$ (15 of 158) 9 %        |
| R134a/DE589(99.0/1.0)   | $X_1, X_3$ (106 of 147) 72 %<br>$X_1$ (25 of 147) 17 %<br>$X_1, X_2$ (9 of 147) 6 %        |
| R134a/DE589(98.0/2.0)   | $X_1, X_3$ (57 of 140) 41 %<br>$X_1, X_2$ (51 of 140) 36 %<br>$X_1$ (20 of 140) 14 %       |
| R134a/DE590(99.5/0.5)   | $X_1, X_3$ (120 of 177) 68 %<br>$X_1$ (27 of 177) 15 %<br>$X_1, X_3, X_5$ (13 of 177) 7 %  |
| R134a/DE590(98.8/1.2)   | $X_1, X_3$ (97 of 205) 47 %<br>$X_1$ (68 of 205) 33 %<br>$X_1, X_3, X_5$ (19 of 205) 9 %   |
| R134a/DE590(97.3/2.7)   | $X_1$ (114 of 259) 44 %<br>$X_1, X_3$ (100 of 259) 39 %<br>$X_1, X_2$ (27 of 259) 10 %     |
| R134a/DE599(99.5/0.5)   | $X_1$ (172 of 206) 83 %<br>$X_1, X_3$ (17 of 206) 8 %<br>$X_1, X_2$ (9 of 206) 4 %         |
| R134a/DE599(98.9/1.1)   | $X_1$ (121 of 146) 83 %<br>$X_1, X_2$ (10 of 146) 7 %<br>$X_1, X_3$ (7 of 146) 5 %         |
| R134a/DE599(97.7/2.3)   | $X_1$ (156 of 170) 92 %<br>$X_1, X_3$ (8 of 170) 4 %<br>$X_1, X_4$ (3 of 170) 2 %          |
| R134a/DE601(99.5/0.5)   | $X_1, X_2$ (117 of 143) 82 %<br>$X_1, X_3$ (8 of 143) 6 %<br>$X_1$ (8 of 143) 6 %          |
| R134a/DE601(98.7/1.3)   | $X_1, X_2$ (109 of 180) 61 %<br>$X_1, X_5$ (28 of 180) 16 %<br>$X_1, X_3$ (23 of 180) 13 % |
| R134a/DE601(96.7/3.3)   | $X_1, X_5$ (62 of 142) 44 %<br>$X_1, X_2$ (39 of 142) 27 %<br>$X_1, X_3$ (22 of 142) 15 %  |
| R134a   | $X_1$ (169 of 391) 43 %<br>$X_1, X_2, X_5$ (90 of 391) 23 %<br>$X_1, X_3$ (38 of 391) 10 % |

Table 3 Pool boiling data

**R134a/DE589  
(99.5/0.5)  
File: DE5895.DAT**

| $\Delta T_c$ (K) | $q''$ (W/m <sup>2</sup> ) |
|------------------|---------------------------|
| 4.903            | 155508.8                  |
| 4.857            | 155284.2                  |
| 4.671            | 147655.0                  |
| 4.646            | 148004.4                  |
| 4.626            | 148911.3                  |
| 4.601            | 148798.6                  |
| 4.348            | 137254.8                  |
| 4.357            | 136166.1                  |
| 3.909            | 119527.8                  |
| 3.886            | 120948.7                  |
| 3.560            | 107266.0                  |
| 3.646            | 108657.2                  |
| 3.659            | 95958.4                   |
| 3.259            | 97831.1                   |
| 3.324            | 84684.6                   |
| 2.892            | 82244.8                   |
| 2.786            | 82244.8                   |
| 2.600            | 76127.9                   |
| 2.584            | 76144.2                   |
| 2.286            | 68172.1                   |
| 2.242            | 67604.5                   |
| 2.043            | 61881.0                   |
| 2.065            | 62077.4                   |
| 4.676            | 153976.6                  |
| 4.685            | 153072.5                  |
| 4.481            | 146744.4                  |
| 4.476            | 148304.0                  |
| 4.240            | 138192.1                  |
| 4.251            | 137828.7                  |
| 3.886            | 123541.0                  |
| 3.914            | 124600.1                  |
| 3.551            | 110655.2                  |
| 3.559            | 110627.5                  |
| 3.160            | 94826.7                   |
| 3.081            | 95028.1                   |
| 2.783            | 85089.7                   |
| 2.808            | 85550.3                   |
| 2.507            | 75332.0                   |
| 2.524            | 74620.8                   |
| 2.096            | 65481.2                   |
| 2.106            | 65943.7                   |
| 1.778            | 57548.3                   |
| 1.813            | 57150.3                   |
| 1.474            | 50416.1                   |
| 1.462            | 50549.3                   |
| 0.879            | 36312.4                   |
| 0.961            | 36375.8                   |
| 0.271            | 8479.6                    |
| 4.712            | 156908.3                  |
| 4.555            | 148755.2                  |
| 4.550            | 151346.3                  |
| 4.634            | 155592.5                  |
| 4.363            | 146245.2                  |
| 4.405            | 146347.6                  |
| 3.967            | 129390.6                  |
| 3.970            | 127635.9                  |
| 3.586            | 114522.0                  |
| 3.787            | 120594.9                  |
| 3.305            | 103883.4                  |
| 4.555            | 148755.2                  |
| 2.968            | 92082.3                   |
| 2.859            | 90538.2                   |
| 2.565            | 79132.4                   |
| 2.593            | 79425.4                   |
| 2.327            | 70983.2                   |
| 2.172            | 69071.4                   |
| 1.631            | 56836.4                   |
| 1.746            | 56683.0                   |
| 1.297            | 47842.7                   |
| 1.352            | 47684.9                   |
| 0.902            | 37998.3                   |
| 0.941            | 36896.9                   |
| 0.653            | 27123.7                   |
| 4.747            | 158421.8                  |
| 4.828            | 162739.0                  |
| 4.709            | 158745.7                  |
| 4.706            | 159902.2                  |
| 4.437            | 147530.8                  |
| 4.437            | 146935.7                  |
| 3.990            | 130112.0                  |
| 4.068            | 131681.7                  |
| 3.796            | 122547.5                  |
| 3.777            | 121967.5                  |
| 3.268            | 100622.6                  |
| 4.828            | 162739.0                  |
| 3.411            | 107651.2                  |
| 3.467            | 110474.3                  |
| 3.107            | 94895.2                   |
| 3.097            | 95509.9                   |
| 2.544            | 76978.1                   |
| 2.421            | 74339.0                   |

|       |          |
|-------|----------|
| 2.179 | 67986.8  |
| 2.169 | 67979.1  |
| 1.961 | 62290.9  |
| 1.940 | 62516.1  |
| 1.560 | 52827.0  |
| 1.609 | 53825.1  |
| 0.840 | 36239.8  |
| 0.905 | 35239.4  |
| 0.469 | 21776.3  |
| 0.502 | 21613.0  |
| 0.201 | 8284.5   |
| 4.593 | 154747.5 |
| 4.671 | 156835.0 |
| 4.617 | 159006.6 |
| 4.336 | 145939.3 |
| 4.341 | 146834.2 |
| 3.937 | 130299.7 |
| 3.965 | 131674.3 |
| 3.718 | 119218.1 |
| 3.679 | 118923.9 |
| 3.378 | 109579.8 |
| 3.406 | 109673.3 |
| 3.152 | 99075.1  |
| 3.141 | 98508.1  |
| 2.734 | 85119.9  |
| 2.665 | 83525.7  |
| 2.440 | 77200.9  |
| 2.478 | 78291.3  |
| 2.154 | 69262.4  |
| 2.173 | 68379.8  |
| 2.082 | 66361.1  |
| 1.539 | 54101.1  |
| 1.561 | 54652.1  |
| 0.932 | 38084.9  |
| 0.955 | 37916.9  |
| 0.611 | 26693.2  |
| 0.509 | 22303.8  |
| 4.638 | 158425.2 |
| 4.630 | 160768.1 |
| 4.469 | 154422.7 |
| 4.481 | 155779.5 |
| 4.128 | 139814.3 |
| 4.104 | 139526.8 |
| 3.744 | 126515.3 |
| 3.776 | 126568.5 |
| 3.308 | 107075.0 |
| 3.372 | 110734.0 |
| 2.930 | 93476.5  |
| 2.904 | 93025.6  |
| 2.433 | 77595.1  |
| 2.337 | 75207.4  |
| 2.181 | 68178.7  |
| 2.125 | 67325.3  |
| 1.833 | 59701.6  |
| 1.877 | 61176.3  |
| 1.811 | 58928.9  |
| 1.630 | 54463.2  |
| 1.291 | 46241.8  |
| 1.290 | 45431.6  |
| 1.109 | 41682.4  |
| 0.697 | 29109.7  |
| 0.583 | 22702.3  |
| 0.462 | 18067.9  |

**R134a/DE589  
(99/1)  
File: DE5891.DAT**

| $\Delta T_c$ (K) | $q''$ (W/m <sup>2</sup> ) |
|------------------|---------------------------|
| 4.796            | 164503.3                  |
| 4.868            | 164929.8                  |
| 4.634            | 153657.9                  |
| 4.572            | 153747.6                  |
| 4.270            | 141232.3                  |
| 4.230            | 140746.0                  |
| 3.884            | 127359.7                  |
| 3.718            | 121280.4                  |
| 3.556            | 113279.1                  |
| 3.585            | 115433.9                  |
| 3.342            | 106998.5                  |
| 3.330            | 107398.3                  |
| 2.963            | 93309.4                   |
| 2.943            | 93158.8                   |
| 2.558            | 79843.7                   |
| 2.615            | 80712.9                   |
| 2.255            | 70945.9                   |
| 2.263            | 70838.1                   |
| 1.962            | 62509.3                   |
| 1.914            | 61051.9                   |
| 1.344            | 46899.6                   |
| 1.342            | 46300.2                   |
| 0.889            | 33555.1                   |
| 4.747            | 167238.0                  |

|       |          |
|-------|----------|
| 4.758 | 169041.8 |
| 4.697 | 170410.1 |
| 4.230 | 148863.9 |
| 4.206 | 148412.9 |
| 3.924 | 133196.7 |
| 3.908 | 133089.1 |
| 3.562 | 121356.9 |
| 3.618 | 121711.9 |
| 3.307 | 109052.3 |
| 3.293 | 109258.1 |
| 3.072 | 99406.3  |
| 3.052 | 99586.6  |
| 2.692 | 86593.4  |
| 2.159 | 70665.6  |
| 2.297 | 73467.0  |
| 2.301 | 74111.1  |
| 2.350 | 75336.9  |
| 2.159 | 70665.6  |
| 2.178 | 70476.5  |
| 1.737 | 58171.3  |
| 1.934 | 58723.8  |
| 1.419 | 44973.4  |
| 1.489 | 44385.6  |
| 0.793 | 26945.9  |
| 0.784 | 26270.8  |
| 4.945 | 155690.7 |
| 4.919 | 157188.8 |
| 4.470 | 139270.4 |
| 4.540 | 141305.7 |
| 4.274 | 132646.0 |
| 4.275 | 132362.0 |
| 3.914 | 118760.5 |
| 3.914 | 118580.6 |
| 3.550 | 106177.0 |
| 3.512 | 105397.7 |
| 2.990 | 88292.6  |
| 3.007 | 89708.1  |
| 2.663 | 80616.8  |
| 2.701 | 81559.3  |
| 2.318 | 72740.0  |
| 2.359 | 72841.2  |
| 1.927 | 62523.3  |
| 1.942 | 61927.5  |
| 1.495 | 51007.6  |
| 1.653 | 50994.1  |
| 1.266 | 40596.9  |
| 1.322 | 40335.1  |
| 0.756 | 27513.4  |
| 1.008 | 26783.2  |
| 0.131 | 8334.6   |
| 4.705 | 152601.2 |
| 4.676 | 155983.2 |
| 4.334 | 138691.6 |
| 4.382 | 139989.8 |
| 4.113 | 129841.0 |
| 4.104 | 130174.9 |
| 3.836 | 120314.6 |
| 3.843 | 120811.0 |
| 3.463 | 107513.0 |
| 3.476 | 108202.7 |
| 3.178 | 99060.5  |
| 3.212 | 99514.6  |
| 2.719 | 84906.5  |
| 2.723 | 84802.4  |
| 2.287 | 72881.1  |
| 2.251 | 72059.2  |
| 2.073 | 62884.4  |
| 1.742 | 52411.8  |
| 1.802 | 52289.7  |
| 1.512 | 44370.6  |
| 1.545 | 44092.1  |
| 1.072 | 34046.5  |
| 1.109 | 34159.3  |
| 0.570 | 22281.5  |
| 4.508 | 145151.5 |
| 4.571 | 147926.6 |
| 4.284 | 138270.1 |
| 4.336 | 140832.9 |
| 4.123 | 133580.4 |
| 4.106 | 134552.8 |
| 3.830 | 125007.9 |
| 3.842 | 126857.1 |
| 3.563 | 114758.4 |
| 3.517 | 113862.6 |
| 3.211 | 104593.6 |
| 3.088 | 99838.1  |
| 2.825 | 90750.3  |
| 2.938 | 93198.7  |
| 2.572 | 82335.6  |
| 2.609 | 82644.0  |
| 2.296 | 73127.9  |
| 2.258 | 71831.0  |
| 1.843 | 60674.8  |
| 1.892 | 61751.6  |
| 1.443 | 49740.1  |
| 1.440 | 49487.4  |

|       |          |
|-------|----------|
| 1.192 | 38865.6  |
| 0.691 | 25276.1  |
| 0.694 | 24593.1  |
| 0.322 | 13839.7  |
| 4.590 | 155336.1 |
| 4.638 | 159404.0 |
| 4.164 | 136971.9 |
| 4.149 | 138870.2 |
| 3.414 | 109500.9 |
| 3.404 | 109704.4 |
| 2.575 | 82932.5  |
| 2.567 | 81781.6  |
| 1.928 | 65849.4  |
| 2.013 | 67700.6  |
| 1.304 | 46709.3  |
| 1.390 | 46060.0  |
| 1.019 | 33566.3  |
| 1.023 | 32629.6  |
| 0.728 | 25245.1  |
| 0.699 | 25283.8  |
| 0.292 | 11624.6  |
| 0.306 | 11143.3  |

**R134a/DE589  
(98/2)  
File: DE5892.DAT**

| $\Delta T_c$ (K) | $q''$ (W/m <sup>2</sup> ) |
|------------------|---------------------------|
| 4.341            | 159658.9                  |
| 4.065            | 149520.9                  |
| 4.165            | 151034.8                  |
| 3.987            | 137003.5                  |
| 3.972            | 136426.1                  |
| 3.717            | 119632.2                  |
| 3.707            | 119368.9                  |
| 3.492            | 108603.6                  |
| 3.467            | 108348.0                  |
| 3.065            | 93032.0                   |
| 4.346            | 155614.7                  |
| 4.315            | 160503.3                  |
| 4.380            | 161441.8                  |
| 4.051            | 142335.5                  |
| 4.090            | 144125.6                  |
| 3.918            | 131498.2                  |
| 3.812            | 131590.9                  |
| 3.592            | 115541.5                  |
| 3.641            | 115018.9                  |
| 3.420            | 104106.4                  |
| 3.450            | 103618.5                  |
| 3.219            | 94153.9                   |
| 3.197            | 92246.0                   |
| 2.902            | 81508.9                   |
| 2.968            | 82337.1                   |
| 2.663            | 72368.2                   |
| 2.657            | 72071.1                   |
| 2.675            | 72381.7                   |
| 2.505            | 63964.3                   |
| 2.522            | 63733.2                   |
| 2.171            | 54181.2                   |
| 2.183            | 53697.0                   |
| 1.819            | 44738.9                   |
| 1.918            | 45359.6                   |
| 1.156            | 28466.1                   |
| 1.126            | 27667.4                   |
| 4.280            | 151915.2                  |
| 4.312            | 155267.5                  |
| 4.017            | 137757.2                  |
| 4.149            | 139156.9                  |
| 3.974            | 127118.5                  |
| 4.120            | 128376.8                  |
| 3.755            | 115584.9                  |
| 3.768            | 116173.2                  |
| 3.449            | 104166.4                  |
| 3.430            | 103811.8                  |
| 2.999            | 92152.3                   |
| 3.064            | 91571.9                   |
| 2.669            | 81819.6                   |
| 2.764            | 82093.5                   |
| 2.486            | 72043.4                   |
| 2.499            | 71320.0                   |
| 2.091            | 60417.9                   |
| 2.080            | 59591.3                   |
| 1.553            | 46992.4                   |
| 1.649            | 47273.2                   |
| 1.054            | 33258.2                   |
| 1.188            | 32459.8                   |
| 0.715            | 21975.4                   |
| 0.770            | 21790.1                   |
| 0.303            | 7861.5                    |
| 4.329            | 156855.7                  |
| 4.375            | 160043.3                  |
| 4.276            | 144339.8                  |
| 4.347            | 146106.8                  |

|       |          |
|-------|----------|
| 4.072 | 130637.9 |
| 4.105 | 131132.5 |
| 3.756 | 115822.6 |
| 3.695 | 115735.9 |
| 3.244 | 98390.2  |
| 3.269 | 100126.0 |
| 2.986 | 91652.1  |
| 3.014 | 91884.4  |
| 2.591 | 80201.7  |
| 2.503 | 77263.2  |
| 2.386 | 72255.7  |
| 2.462 | 72322.6  |
| 2.078 | 61801.8  |
| 2.140 | 61542.8  |
| 1.779 | 51720.6  |
| 1.844 | 51824.5  |
| 1.529 | 43566.1  |
| 1.653 | 43258.2  |
| 1.231 | 33629.0  |
| 4.407 | 150271.5 |
| 4.446 | 150540.8 |
| 4.277 | 135157.1 |
| 4.271 | 135581.0 |
| 3.983 | 122437.3 |
| 3.939 | 123706.1 |
| 3.626 | 111416.1 |
| 3.628 | 111584.4 |
| 3.365 | 101780.4 |
| 3.345 | 101292.4 |
| 2.866 | 84691.0  |
| 2.814 | 84368.4  |
| 2.488 | 71976.4  |
| 2.599 | 73049.4  |
| 2.229 | 62688.1  |
| 2.295 | 63303.3  |
| 1.799 | 49335.6  |
| 1.779 | 48432.6  |
| 1.533 | 41372.6  |
| 1.559 | 41258.6  |
| 1.060 | 28668.5  |
| 1.052 | 27672.0  |
| 0.853 | 22960.0  |
| 0.672 | 19369.4  |
| 0.535 | 14120.6  |
| 4.362 | 162965.3 |
| 4.418 | 164824.2 |
| 4.101 | 145949.5 |
| 4.192 | 146600.0 |
| 3.978 | 132056.3 |
| 4.031 | 132370.7 |
| 3.826 | 120051.0 |
| 3.870 | 119410.0 |
| 3.493 | 108338.2 |
| 3.556 | 108360.6 |
| 3.040 | 91583.5  |
| 3.252 | 94718.8  |
| 2.931 | 83516.0  |
| 2.943 | 84022.2  |
| 2.616 | 73598.9  |
| 2.541 | 70409.9  |
| 2.337 | 63705.6  |
| 2.443 | 64134.3  |
| 1.887 | 50535.3  |
| 2.007 | 50377.7  |
| 1.488 | 38411.8  |
| 1.625 | 39359.6  |
| 0.913 | 26277.6  |
| 0.967 | 26520.1  |
| 0.388 | 12638.5  |
| 0.397 | 12209.6  |

**R134a/DE590  
(99.5/0.5)  
File: DE5905.DAT**

| $\Delta T_c$ (K) | $q''$ (W/m <sup>2</sup> ) |
|------------------|---------------------------|
| 4.592            | 140998.4                  |
| 4.691            | 147000.8                  |
| 4.050            | 119915.8                  |
| 4.045            | 119781.9                  |
| 3.615            | 103060.9                  |
| 3.713            | 106075.1                  |
| 3.512            | 98410.4                   |
| 3.522            | 98312.8                   |
| 3.295            | 91298.8                   |
| 3.104            | 86880.1                   |
| 2.926            | 79590.6                   |
| 2.925            | 80046.9                   |
| 2.408            | 67745.3                   |
| 2.408            | 67864.7                   |
| 1.863            | 54646.2                   |
| 1.910            | 55578.4                   |
| 1.577            | 49401.0                   |
| 1.602            | 49503.9                   |
| 1.338            | 41120.7                   |
| 1.256            | 39158.4                   |
| 0.897            | 33333.6                   |
| 0.949            | 33626.0                   |
| 0.676            | 23120.4                   |

|       |          |
|-------|----------|
| 4.332 | 139768.1 |
| 4.315 | 139718.5 |
| 3.921 | 122299.9 |
| 3.896 | 120817.2 |
| 3.582 | 108017.0 |
| 3.599 | 108376.3 |
| 3.334 | 98016.5  |
| 3.344 | 98111.5  |
| 2.847 | 84268.3  |
| 2.860 | 84060.4  |
| 2.539 | 75809.2  |
| 2.491 | 73564.5  |
| 2.226 | 67328.0  |
| 2.226 | 67891.4  |
| 1.839 | 56035.2  |
| 1.821 | 55620.3  |
| 1.489 | 49729.4  |
| 1.475 | 48989.9  |
| 1.309 | 44485.0  |
| 1.303 | 44344.2  |
| 0.965 | 35262.9  |
| 0.961 | 34952.7  |
| 0.595 | 25012.4  |
| 4.335 | 146426.1 |
| 4.294 | 146734.3 |
| 4.118 | 137009.2 |
| 4.075 | 133228.1 |
| 3.736 | 118912.3 |
| 3.764 | 119628.4 |
| 3.424 | 106649.2 |
| 3.398 | 106661.9 |
| 3.031 | 92092.4  |
| 3.139 | 93799.2  |
| 2.692 | 84054.5  |
| 2.708 | 82927.4  |
| 2.385 | 75381.0  |
| 2.408 | 74329.3  |
| 2.060 | 65291.2  |
| 2.129 | 65035.7  |
| 1.588 | 54178.3  |
| 1.592 | 53897.4  |
| 1.290 | 46091.0  |
| 1.291 | 44909.6  |
| 1.031 | 38875.7  |
| 1.046 | 39241.3  |
| 0.630 | 25790.4  |
| 4.201 | 141052.8 |
| 4.210 | 141412.6 |
| 3.813 | 126955.0 |
| 3.820 | 126334.1 |
| 3.485 | 112735.0 |
| 3.490 | 111492.5 |
| 3.013 | 94525.9  |
| 3.000 | 94226.6  |
| 2.745 | 86525.2  |
| 2.761 | 86365.9  |
| 2.370 | 74865.2  |
| 2.368 | 75273.4  |
| 1.971 | 64993.4  |
| 1.946 | 65805.5  |
| 1.593 | 54490.8  |
| 1.620 | 54349.4  |
| 1.148 | 44205.5  |
| 1.128 | 44525.1  |
| 0.906 | 36818.1  |
| 0.921 | 36640.9  |
| 0.499 | 23376.7  |
| 4.345 | 139336.1 |
| 4.387 | 143016.8 |
| 3.963 | 124396.5 |
| 3.896 | 124305.3 |
| 3.647 | 114057.4 |
| 3.653 | 113716.3 |
| 3.431 | 106121.7 |
| 3.496 | 107570.2 |
| 3.132 | 94919.2  |
| 3.136 | 94615.0  |
| 2.762 | 83343.2  |
| 2.770 | 82394.0  |
| 2.362 | 72572.6  |
| 2.338 | 73192.1  |
| 2.078 | 64419.4  |
| 2.103 | 64528.5  |
| 1.632 | 54421.3  |
| 1.674 | 54769.6  |
| 1.373 | 45831.2  |
| 1.386 | 45253.1  |
| 0.882 | 33819.5  |
| 4.302 | 143066.4 |
| 4.351 | 147231.0 |
| 3.711 | 118468.9 |
| 3.701 | 117744.7 |
| 3.353 | 104307.8 |
| 4.500 | 150197.8 |
| 4.545 | 152600.6 |
| 4.546 | 154351.4 |
| 4.177 | 140892.4 |
| 4.208 | 141971.3 |
| 3.983 | 130392.1 |
| 3.997 | 130188.4 |
| 3.777 | 121582.8 |
| 3.702 | 118834.7 |
| 3.514 | 111326.5 |

|       |          |
|-------|----------|
| 3.492 | 111337.4 |
| 3.533 | 111051.3 |
| 3.484 | 109569.7 |
| 3.202 | 98769.2  |
| 3.171 | 98061.3  |
| 2.840 | 84631.9  |
| 2.884 | 86533.1  |
| 2.430 | 74499.9  |
| 2.489 | 74188.7  |
| 2.505 | 75067.6  |
| 2.071 | 62435.8  |
| 2.033 | 62099.0  |
| 1.746 | 56172.4  |
| 1.778 | 56205.1  |
| 1.213 | 38979.3  |
| 1.291 | 38698.8  |
| 4.577 | 156056.6 |
| 4.615 | 158997.7 |
| 4.123 | 137629.9 |
| 4.131 | 137295.7 |
| 3.719 | 120880.2 |
| 3.632 | 116282.9 |
| 3.452 | 108463.6 |
| 3.470 | 109587.7 |
| 3.047 | 94631.6  |
| 4.747 | 157212.0 |
| 4.759 | 159685.5 |
| 3.853 | 121687.1 |
| 3.744 | 117738.1 |
| 2.596 | 74160.0  |
| 2.529 | 74296.8  |
| 1.222 | 41025.0  |
| 1.268 | 41472.4  |
| 0.813 | 31457.3  |
| 0.860 | 30572.5  |
| 0.753 | 25786.7  |
| 0.678 | 23878.7  |
| 0.629 | 24152.1  |
| 0.530 | 21425.0  |
| 0.550 | 21511.3  |
| 0.483 | 19423.8  |
| 0.365 | 15245.7  |
| 0.341 | 14503.8  |

**R134a/DE590  
(98.8/1.2)  
File: DE5901.DAT**

| $\Delta T_c$ (K) | $q''$ (W/m <sup>2</sup> ) |
|------------------|---------------------------|
| 6.501            | 153034.9                  |
| 6.430            | 153206.0                  |
| 5.810            | 138117.1                  |
| 5.820            | 138430.6                  |
| 5.213            | 124948.8                  |
| 5.033            | 120259.2                  |
| 4.766            | 114089.6                  |
| 4.894            | 116420.1                  |
| 4.520            | 105668.6                  |
| 4.454            | 101935.0                  |
| 4.148            | 90946.0                   |
| 4.263            | 92585.9                   |
| 3.820            | 81359.4                   |
| 3.832            | 81885.8                   |
| 3.402            | 69226.8                   |
| 3.278            | 66466.3                   |
| 2.714            | 56691.1                   |
| 2.722            | 56680.4                   |
| 1.952            | 44683.0                   |
| 1.967            | 44773.4                   |
| 1.358            | 32974.6                   |
| 1.242            | 31600.6                   |
| 0.769            | 24498.9                   |
| 0.844            | 25197.5                   |
| 0.447            | 13045.1                   |
| 5.337            | 151453.9                  |
| 5.153            | 147962.4                  |
| 5.027            | 145478.5                  |
| 5.136            | 149329.2                  |
| 4.737            | 138293.4                  |
| 4.735            | 138623.2                  |
| 4.510            | 130762.6                  |
| 4.330            | 123737.9                  |
| 4.265            | 117648.5                  |
| 4.344            | 118907.1                  |
| 4.113            | 110146.0                  |
| 4.154            | 110259.3                  |
| 3.652            | 93468.0                   |
| 3.771            | 96237.9                   |
| 3.280            | 83051.6                   |
| 3.303            | 82906.1                   |
| 2.944            | 72919.4                   |
| 2.968            | 72744.7                   |
| 2.648            | 63412.8                   |
| 2.645            | 63080.9                   |
| 2.152            | 52168.2                   |
| 2.131            | 51919.8                   |
| 1.454            | 39441.9                   |
| 1.537            | 39440.1                   |
| 1.015            | 27014.2                   |
| 5.152            | 154547.9                  |
| 4.881            | 148664.6                  |

|       |          |
|-------|----------|
| 4.685 | 144351.1 |
| 4.725 | 149368.4 |
| 4.328 | 135068.8 |
| 4.328 | 135297.7 |
| 4.051 | 123625.0 |
| 4.086 | 124226.8 |
| 3.833 | 116896.4 |
| 3.835 | 116768.8 |
| 3.645 | 108310.3 |
| 3.717 | 106630.5 |
| 3.405 | 95198.4  |
| 3.427 | 94293.9  |
| 2.987 | 80863.5  |
| 3.023 | 80987.3  |
| 2.511 | 65818.6  |
| 2.563 | 67449.8  |
| 2.142 | 58126.8  |
| 2.146 | 57949.2  |
| 1.554 | 43343.9  |
| 1.562 | 44625.1  |
| 1.010 | 33168.5  |
| 1.052 | 32805.3  |
| 0.531 | 18073.3  |
| 4.747 | 152062.1 |
| 4.809 | 157819.2 |
| 4.450 | 143989.4 |
| 4.511 | 147028.6 |
| 4.172 | 135527.6 |
| 4.160 | 135318.6 |
| 3.869 | 123869.7 |
| 3.746 | 117329.7 |
| 3.609 | 110536.9 |
| 3.670 | 112961.4 |
| 3.406 | 102566.3 |
| 3.436 | 102668.6 |
| 2.988 | 84399.4  |
| 2.929 | 82504.3  |
| 2.619 | 72897.9  |
| 2.577 | 71789.7  |
| 2.065 | 57641.7  |
| 2.060 | 58690.3  |
| 1.832 | 53612.6  |
| 1.879 | 53388.9  |
| 1.590 | 45698.8  |
| 1.558 | 44838.2  |
| 0.794 | 27834.6  |
| 0.831 | 28228.3  |
| 0.496 | 18443.7  |
| 4.894 | 155785.8 |
| 4.889 | 161644.0 |
| 4.361 | 140505.4 |
| 4.348 | 140442.5 |
| 3.988 | 124729.1 |
| 4.070 | 127109.9 |
| 3.891 | 119395.6 |
| 3.932 | 120185.8 |
| 3.548 | 106467.7 |
| 3.555 | 106474.9 |
| 3.178 | 91725.2  |
| 3.208 | 92067.6  |
| 2.623 | 74719.0  |
| 2.687 | 75922.1  |
| 2.299 | 64096.6  |
| 2.275 | 64576.0  |
| 1.939 | 56733.8  |
| 1.939 | 56644.2  |
| 1.823 | 52443.6  |
| 1.835 | 52476.6  |
| 1.130 | 37473.2  |
| 1.226 | 36904.5  |
| 0.696 | 21942.6  |
| 4.825 | 153994.3 |
| 4.722 | 153103.2 |
| 4.649 | 152633.9 |
| 4.186 | 135903.3 |
| 4.146 | 135083.2 |
| 4.003 | 120347.8 |
| 3.990 | 121181.4 |
| 3.690 | 111011.1 |
| 3.706 | 110717.7 |
| 3.434 | 97831.7  |
| 3.341 | 94654.7  |
| 3.233 | 90296.4  |
| 3.299 | 91914.7  |
| 2.918 | 77094.1  |
| 2.686 | 77623.7  |
| 2.639 | 73844.0  |
| 2.644 | 73023.5  |
| 2.682 | 73069.5  |
| 2.078 | 61170.6  |
| 2.138 | 61777.4  |
| 1.366 | 43813.3  |
| 1.306 | 44038.9  |
| 0.761 | 24221.7  |
| 0.761 | 24025.0  |
| 4.608 | 149639.7 |
| 4.585 | 151100.7 |
| 4.261 | 140631.7 |
| 4.257 | 140361.9 |
| 4.027 | 130995.1 |
| 3.998 | 128441.9 |
| 3.738 | 117723.6 |
| 3.783 | 118774.6 |

|       |          |
|-------|----------|
| 3.554 | 108459.9 |
| 3.554 | 108319.9 |
| 3.253 | 95736.0  |
| 3.346 | 99491.7  |
| 3.116 | 90925.9  |
| 3.084 | 89733.6  |
| 2.768 | 79096.3  |
| 2.828 | 80514.9  |
| 2.579 | 74463.9  |
| 2.606 | 74445.4  |
| 1.395 | 42571.2  |
| 1.383 | 42880.7  |
| 1.409 | 42719.5  |
| 4.514 | 149592.0 |
| 4.495 | 150933.0 |
| 4.210 | 140848.0 |
| 4.195 | 141474.7 |
| 3.919 | 129555.6 |
| 3.873 | 129129.9 |
| 3.626 | 117575.3 |
| 3.648 | 118383.1 |
| 3.485 | 109696.9 |
| 3.496 | 109782.8 |
| 3.192 | 98871.9  |
| 3.220 | 98369.1  |
| 2.983 | 89604.4  |
| 3.084 | 92402.8  |
| 2.632 | 80337.5  |
| 2.670 | 80720.9  |
| 2.278 | 66531.5  |
| 2.186 | 66527.2  |
| 1.945 | 59487.1  |
| 2.005 | 59872.1  |
| 1.847 | 55521.3  |
| 1.848 | 55473.6  |
| 1.246 | 39492.8  |
| 1.291 | 39892.9  |
| 0.526 | 16803.2  |
| 0.526 | 15947.3  |

**R134a/DE590**  
**(97.3/2.7)**  
**File: DE5902.DAT**

| $\Delta T_c$ (K) | $q''$ (W/m <sup>2</sup> ) |
|------------------|---------------------------|
| 7.224            | 134024.3                  |
| 7.377            | 137130.5                  |
| 7.052            | 130203.8                  |
| 7.070            | 132160.1                  |
| 6.664            | 123773.0                  |
| 6.661            | 123743.5                  |
| 6.307            | 114910.6                  |
| 6.258            | 112745.4                  |
| 5.799            | 101239.8                  |
| 5.958            | 102644.8                  |
| 5.615            | 96938.0                   |
| 5.661            | 97688.9                   |
| 5.199            | 93156.7                   |
| 5.114            | 93214.8                   |
| 4.581            | 83725.8                   |
| 4.564            | 83396.9                   |
| 3.903            | 73504.1                   |
| 4.011            | 74649.2                   |
| 3.629            | 67411.2                   |
| 3.646            | 67703.3                   |
| 2.741            | 53463.0                   |
| 2.804            | 53300.0                   |
| 2.087            | 40492.4                   |
| 7.126            | 139554.4                  |
| 7.207            | 141903.6                  |
| 6.879            | 131145.2                  |
| 6.951            | 130107.5                  |
| 6.313            | 113370.0                  |
| 6.252            | 111297.3                  |
| 6.060            | 105148.6                  |
| 6.094            | 105465.7                  |
| 5.653            | 95396.0                   |
| 5.635            | 95216.0                   |
| 5.136            | 87382.4                   |
| 5.150            | 87329.8                   |
| 4.686            | 79688.9                   |
| 4.787            | 81182.6                   |
| 4.359            | 73619.6                   |
| 4.412            | 74535.4                   |
| 3.647            | 63128.1                   |
| 3.674            | 62519.9                   |
| 3.219            | 54500.6                   |
| 3.274            | 54765.7                   |
| 2.789            | 47020.0                   |
| 2.805            | 46744.9                   |
| 2.231            | 39069.5                   |
| 2.281            | 38956.5                   |
| 1.532            | 26755.7                   |
| 6.155            | 145489.5                  |
| 6.189            | 149416.6                  |
| 6.041            | 140162.0                  |
| 6.044            | 141894.3                  |
| 5.915            | 130483.0                  |
| 5.954            | 129812.8                  |
| 5.585            | 116858.0                  |
| 5.712            | 119622.7                  |
| 5.376            | 110147.6                  |

|       |          |
|-------|----------|
| 5.430 | 109526.1 |
| 5.302 | 105271.5 |
| 5.304 | 103201.9 |
| 4.875 | 92476.3  |
| 4.853 | 92048.7  |
| 4.496 | 85805.9  |
| 4.583 | 86831.1  |
| 4.326 | 82279.6  |
| 4.345 | 82539.3  |
| 3.881 | 73454.0  |
| 3.825 | 72594.1  |
| 3.657 | 69029.8  |
| 3.672 | 69544.7  |
| 3.607 | 58672.2  |
| 3.080 | 58310.9  |
| 5.874 | 145608.2 |
| 5.864 | 146859.5 |
| 5.171 | 124946.4 |
| 5.324 | 125155.9 |
| 5.100 | 116249.7 |
| 5.113 | 115418.2 |
| 4.798 | 106636.8 |
| 4.870 | 108040.5 |
| 4.616 | 101536.4 |
| 4.608 | 101101.0 |
| 4.205 | 90880.7  |
| 4.204 | 90786.1  |
| 3.932 | 84360.8  |
| 3.808 | 82110.7  |
| 3.538 | 76596.3  |
| 3.629 | 77487.4  |
| 3.284 | 69896.9  |
| 3.276 | 69351.6  |
| 2.911 | 60746.9  |
| 2.865 | 59465.1  |
| 2.429 | 51570.7  |
| 2.444 | 51754.7  |
| 1.775 | 38376.8  |
| 1.774 | 37857.3  |
| 1.139 | 26351.6  |
| 5.689 | 147744.7 |
| 5.674 | 146922.1 |
| 5.735 | 149102.9 |
| 5.275 | 130738.0 |
| 5.292 | 129345.1 |
| 4.770 | 115129.0 |
| 4.773 | 115120.8 |
| 4.387 | 103076.0 |
| 4.434 | 103583.5 |
| 4.072 | 93944.5  |
| 4.036 | 93667.9  |
| 3.593 | 83872.0  |
| 3.667 | 84423.0  |
| 3.253 | 74658.3  |
| 3.247 | 73878.9  |
| 3.261 | 74285.4  |
| 3.048 | 69278.4  |
| 3.000 | 68454.0  |
| 2.773 | 63335.6  |
| 2.782 | 63316.3  |
| 2.185 | 50251.6  |
| 2.170 | 49989.1  |
| 1.458 | 34124.1  |
| 1.473 | 34128.5  |
| 5.540 | 146488.2 |
| 5.619 | 156538.4 |
| 5.265 | 144371.1 |
| 5.281 | 143939.1 |
| 4.957 | 131097.3 |
| 4.894 | 126062.4 |
| 4.749 | 120062.4 |
| 4.760 | 119560.8 |
| 4.315 | 105647.6 |
| 4.285 | 104800.5 |
| 3.940 | 95386.9  |
| 3.951 | 95743.3  |
| 3.432 | 83795.3  |
| 3.501 | 83384.9  |
| 3.015 | 72668.1  |
| 2.947 | 70741.1  |
| 2.729 | 64802.0  |
| 2.744 | 64646.8  |
| 2.411 | 56948.3  |
| 2.413 | 56655.9  |
| 1.509 | 36005.9  |
| 1.543 | 35640.5  |
| 1.064 | 24883.5  |
| 5.273 | 147719.7 |
| 5.330 | 150848.0 |
| 5.081 | 141014.7 |
| 5.130 | 140826.3 |
| 4.759 | 129467.1 |
| 4.848 | 130530.7 |
| 4.213 | 112698.1 |
| 4.182 | 112211.7 |
| 3.716 | 97871.7  |
| 3.736 | 97897.2  |
| 3.415 | 90458.7  |
| 3.355 | 88267.2  |
| 3.065 | 80253.6  |
| 3.180 | 82156.6  |
| 2.965 | 76674.3  |
| 2.968 | 76134.9  |

|       |          |
|-------|----------|
| 2.519 | 63343.5  |
| 2.495 | 62963.1  |
| 2.032 | 50519.1  |
| 2.131 | 50062.7  |
| 1.283 | 30536.4  |
| 5.210 | 15985.2  |
| 5.176 | 159280.5 |
| 4.965 | 145464.0 |
| 5.050 | 146321.5 |
| 4.775 | 135452.7 |
| 4.756 | 134370.1 |
| 4.357 | 120675.1 |
| 4.149 | 114735.5 |
| 3.926 | 104829.8 |
| 3.967 | 106561.5 |
| 3.632 | 97548.1  |
| 3.653 | 97024.5  |
| 3.254 | 86182.0  |
| 3.220 | 84656.2  |
| 2.892 | 72913.4  |
| 2.858 | 72312.4  |
| 1.965 | 47585.6  |
| 2.000 | 47080.4  |
| 1.238 | 25847.7  |
| 5.041 | 147850.4 |
| 4.966 | 147194.8 |
| 4.673 | 133218.6 |
| 4.772 | 134625.2 |
| 4.657 | 127815.6 |
| 4.681 | 127800.5 |
| 4.324 | 116833.1 |
| 4.274 | 115529.1 |
| 4.055 | 107129.3 |
| 4.041 | 107140.0 |
| 3.510 | 92833.5  |
| 3.478 | 92178.2  |
| 3.083 | 80060.5  |
| 3.118 | 80517.6  |
| 2.252 | 55755.1  |
| 5.193 | 157543.3 |
| 5.169 | 157539.5 |
| 4.911 | 141400.3 |
| 4.980 | 140489.1 |
| 4.591 | 125594.1 |
| 4.679 | 127300.0 |
| 4.421 | 117748.7 |
| 4.414 | 117470.1 |
| 4.053 | 106042.0 |
| 4.107 | 107736.8 |
| 3.778 | 99910.4  |
| 3.804 | 99864.8  |
| 3.381 | 88598.6  |
| 3.345 | 86818.2  |
| 3.108 | 79391.5  |
| 3.111 | 79014.4  |
| 2.593 | 64642.7  |
| 2.591 | 64114.7  |
| 2.264 | 56019.1  |
| 2.330 | 57334.3  |
| 2.069 | 51817.1  |
| 2.152 | 50474.7  |
| 1.896 | 46729.4  |
| 1.957 | 46215.3  |
| 4.778 | 146812.6 |
| 4.862 | 148981.0 |
| 4.382 | 131403.0 |
| 4.481 | 130939.3 |
| 4.131 | 117616.8 |
| 4.132 | 115763.2 |
| 3.768 | 106705.7 |
| 3.874 | 108836.4 |
| 3.486 | 96365.6  |
| 3.455 | 95137.3  |
| 3.067 | 83829.5  |
| 3.077 | 83416.7  |
| 2.681 | 73315.9  |
| 2.746 | 72367.0  |
| 2.639 | 68472.0  |
| 2.686 | 69765.1  |
| 2.218 | 58266.2  |
| 2.272 | 57541.4  |
| 1.999 | 51369.1  |
| 2.041 | 50894.4  |
| 1.838 | 46047.5  |
| 1.864 | 46695.8  |
| 1.500 | 36144.5  |
| 2.948 | 74236.1  |
| 2.812 | 71901.3  |
| 2.101 | 55196.5  |
| 2.147 | 55377.0  |
| 1.872 | 46109.2  |
| 1.862 | 45714.5  |
| 1.328 | 33154.8  |
| 1.363 | 32223.6  |
| 1.000 | 24848.3  |
| 1.052 | 23843.3  |
| 0.705 | 20366.4  |
| 0.812 | 18810.0  |
| 0.647 | 17356.4  |
| 0.668 | 17683.5  |
| 1.051 | 23333.3  |
| 1.046 | 23807.4  |
| 1.107 | 25583.7  |

|       |         |
|-------|---------|
| 1.144 | 25877.8 |
|-------|---------|

**R134a/DE599**  
**(99.5/0.5)**  
**File: DE5995.DAT**

| $\Delta T_c$ (K) | $q''$ (W/m <sup>2</sup> ) |
|------------------|---------------------------|
| 2.487            | 61255.1                   |
| 2.050            | 51292.6                   |
| 5.250            | 157386.0                  |
| 5.210            | 155886.2                  |
| 4.973            | 142368.0                  |
| 5.046            | 145747.6                  |
| 4.390            | 121526.2                  |
| 4.558            | 125252.3                  |
| 4.031            | 111412.8                  |
| 4.037            | 111138.6                  |
| 3.719            | 99531.9                   |
| 3.701            | 99139.6                   |
| 3.144            | 86767.3                   |
| 3.149            | 84527.6                   |
| 2.775            | 75853.7                   |
| 5.001            | 157745.0                  |
| 5.010            | 159642.4                  |
| 4.843            | 159820.8                  |
| 4.812            | 159597.3                  |
| 4.811            | 157874.5                  |
| 4.715            | 148001.9                  |
| 4.840            | 150930.0                  |
| 4.221            | 122772.6                  |
| 4.290            | 124810.3                  |
| 3.667            | 105497.7                  |
| 3.719            | 104813.1                  |
| 3.228            | 90142.6                   |
| 3.238            | 90599.7                   |
| 2.894            | 80672.6                   |
| 2.994            | 82595.3                   |
| 2.562            | 72404.4                   |
| 2.609            | 72261.6                   |
| 2.595            | 72340.6                   |
| 1.983            | 55366.4                   |
| 2.009            | 55926.7                   |
| 1.577            | 43647.5                   |
| 5.208            | 161665.7                  |
| 5.128            | 162986.4                  |
| 4.572            | 131585.8                  |
| 4.711            | 137466.1                  |
| 4.113            | 117221.0                  |
| 4.116            | 118003.2                  |
| 3.573            | 100385.9                  |
| 3.549            | 100300.3                  |
| 2.926            | 81830.0                   |
| 3.014            | 85947.4                   |
| 2.510            | 74294.4                   |
| 2.551            | 70550.4                   |
| 2.134            | 62056.9                   |
| 4.767            | 152149.0                  |
| 4.834            | 155652.7                  |
| 4.550            | 144466.5                  |
| 4.613            | 145218.0                  |
| 4.370            | 132807.3                  |
| 4.368            | 132502.8                  |
| 4.119            | 121411.9                  |
| 4.129            | 122178.9                  |
| 3.737            | 110703.2                  |
| 3.735            | 110284.9                  |
| 3.186            | 93346.2                   |
| 3.169            | 93018.5                   |
| 2.770            | 81371.0                   |
| 2.748            | 81200.4                   |
| 2.264            | 68051.7                   |
| 2.313            | 68935.4                   |
| 1.826            | 55912.2                   |
| 1.873            | 56352.6                   |
| 1.380            | 41849.2                   |
| 1.387            | 40606.5                   |
| 0.425            | 8609.8                    |
| 4.769            | 150221.5                  |
| 4.817            | 150783.7                  |
| 4.484            | 135089.0                  |
| 4.464            | 134581.9                  |
| 4.166            | 123331.3                  |
| 4.205            | 123128.3                  |
| 3.805            | 111183.7                  |
| 3.821            | 111421.6                  |
| 3.409            | 98965.4                   |
| 3.393            | 98837.0                   |
| 2.918            | 84997.0                   |
| 2.945            | 85025.8                   |
| 2.475            | 72774.7                   |
| 2.477            | 72230.8                   |
| 2.306            | 65954.5                   |
| 2.270            | 65841.3                   |
| 1.863            | 54458.8                   |
| 1.926            | 54834.7                   |
| 1.748            | 48696.2                   |
| 1.768            | 48665.1                   |
| 1.414            | 39207.0                   |
| 1.413            | 39101.8                   |
| 1.201            | 32138.7                   |
| 1.222            | 31954.3                   |
| 1.045            | 24562.0                   |

|       |          |
|-------|----------|
| 1.065 | 24409.6  |
| 0.818 | 16628.8  |
| 0.833 | 16558.8  |
| 0.618 | 10961.9  |
| 4.811 | 155101.5 |
| 4.872 | 160330.7 |
| 4.537 | 143771.9 |
| 4.555 | 142972.1 |
| 4.265 | 127524.6 |
| 4.206 | 125851.8 |
| 4.082 | 119987.2 |
| 4.109 | 121707.3 |
| 3.582 | 104338.1 |
| 3.621 | 104517.4 |
| 3.160 | 91297.1  |
| 3.271 | 93517.8  |
| 2.697 | 76394.7  |
| 2.630 | 76132.6  |
| 2.283 | 66775.6  |
| 2.324 | 67267.1  |
| 1.955 | 56250.4  |
| 1.952 | 56075.8  |
| 1.619 | 46196.2  |
| 1.628 | 45815.0  |
| 1.250 | 36078.0  |
| 1.239 | 36027.7  |
| 1.055 | 28042.5  |
| 1.024 | 27149.3  |
| 4.603 | 154231.6 |
| 4.546 | 153622.6 |
| 4.286 | 137355.4 |
| 4.319 | 138328.3 |
| 4.161 | 129198.6 |
| 4.185 | 130465.6 |
| 3.928 | 120600.5 |
| 3.931 | 120397.4 |
| 3.708 | 109651.2 |
| 3.696 | 109360.1 |
| 3.251 | 96122.3  |
| 3.238 | 95605.7  |
| 3.019 | 87439.4  |
| 2.973 | 87215.5  |
| 2.688 | 76759.7  |
| 2.658 | 75752.6  |
| 2.139 | 63008.5  |
| 2.190 | 64163.9  |
| 1.970 | 57188.1  |
| 1.977 | 57066.4  |
| 1.675 | 48309.3  |
| 1.665 | 47863.4  |
| 1.327 | 36751.2  |
| 1.345 | 37035.3  |
| 1.092 | 29926.5  |
| 5.107 | 159660.8 |
| 5.082 | 160911.3 |
| 4.774 | 147054.9 |
| 4.691 | 141380.1 |
| 4.364 | 127795.5 |
| 4.397 | 128472.6 |
| 4.117 | 118684.0 |
| 4.133 | 118918.0 |
| 3.955 | 111806.9 |
| 3.950 | 111822.6 |
| 3.353 | 96577.8  |
| 3.501 | 99483.3  |
| 3.032 | 85894.7  |
| 3.006 | 85602.4  |
| 2.555 | 73767.0  |
| 2.588 | 74365.7  |
| 2.217 | 64570.2  |
| 2.229 | 64502.0  |
| 2.017 | 57177.6  |
| 1.968 | 56056.4  |
| 1.570 | 44697.4  |
| 1.563 | 44633.4  |
| 1.118 | 32139.6  |
| 4.818 | 160863.1 |
| 4.836 | 160740.4 |
| 4.828 | 160331.2 |
| 4.270 | 130806.5 |
| 4.258 | 130160.4 |
| 3.626 | 109417.0 |
| 3.689 | 110807.3 |
| 3.246 | 97175.2  |
| 3.310 | 97276.7  |
| 2.791 | 84410.1  |
| 2.773 | 84041.1  |
| 2.400 | 74192.9  |
| 2.393 | 73475.6  |
| 2.389 | 74062.4  |
| 1.844 | 57142.2  |
| 1.780 | 55075.2  |
| 1.410 | 46603.0  |
| 1.483 | 46652.6  |
| 1.234 | 36578.1  |
| 1.219 | 36643.7  |
| 0.872 | 27812.6  |
| 0.934 | 28412.4  |
| 0.782 | 18914.8  |
| 0.758 | 18613.2  |
| 0.792 | 18304.9  |
| 0.547 | 11973.8  |
| 0.566 | 11817.8  |

**R134a/DE599**  
(98.9/1.1)  
File: DE5991.DAT

| $\Delta T_c$ (K) | $q''$ (W/m <sup>2</sup> ) |
|------------------|---------------------------|
| 5.096            | 150472.4                  |
| 5.089            | 150578.5                  |
| 4.834            | 136561.0                  |
| 4.800            | 136702.9                  |
| 4.478            | 125296.1                  |
| 4.520            | 125654.4                  |
| 4.138            | 112620.6                  |
| 4.129            | 111803.6                  |
| 3.905            | 104137.6                  |
| 3.919            | 105013.7                  |
| 3.410            | 90751.0                   |
| 3.378            | 90303.4                   |
| 3.047            | 80526.3                   |
| 3.127            | 82563.4                   |
| 2.652            | 69560.9                   |
| 5.432            | 149989.3                  |
| 5.451            | 150687.8                  |
| 5.087            | 136134.4                  |
| 5.150            | 137292.0                  |
| 4.848            | 125385.8                  |
| 4.876            | 125374.3                  |
| 4.438            | 113022.3                  |
| 4.514            | 113631.2                  |
| 4.144            | 101809.1                  |
| 4.164            | 101485.8                  |
| 3.711            | 90809.9                   |
| 3.689            | 89344.7                   |
| 3.322            | 78452.6                   |
| 3.324            | 78207.1                   |
| 2.938            | 68037.0                   |
| 2.924            | 68198.1                   |
| 2.467            | 57019.3                   |
| 2.508            | 56774.9                   |
| 2.071            | 47732.8                   |
| 2.087            | 47636.2                   |
| 1.619            | 37545.2                   |
| 1.689            | 37837.4                   |
| 1.535            | 32751.5                   |
| 1.503            | 32892.1                   |
| 1.155            | 22476.3                   |
| 5.132            | 153751.2                  |
| 5.128            | 155023.1                  |
| 4.845            | 140870.2                  |
| 4.879            | 141771.3                  |
| 4.569            | 130844.8                  |
| 4.607            | 131460.9                  |
| 4.315            | 122664.6                  |
| 4.369            | 121824.9                  |
| 4.029            | 109400.8                  |
| 3.916            | 107701.6                  |
| 3.622            | 96357.5                   |
| 3.675            | 97654.4                   |
| 3.237            | 87144.9                   |
| 3.207            | 86660.1                   |
| 2.809            | 74598.7                   |
| 2.870            | 75726.2                   |
| 2.502            | 65093.2                   |
| 2.506            | 64818.5                   |
| 2.172            | 57506.0                   |
| 2.229            | 57507.3                   |
| 1.800            | 47091.0                   |
| 1.731            | 46520.6                   |
| 1.443            | 38751.5                   |
| 1.487            | 38982.4                   |
| 1.084            | 28105.5                   |
| 5.201            | 161286.4                  |
| 5.190            | 161026.3                  |
| 4.810            | 144131.8                  |
| 4.850            | 143883.5                  |
| 4.601            | 130548.4                  |
| 4.604            | 132100.1                  |
| 4.300            | 120698.4                  |
| 4.298            | 120120.6                  |
| 3.937            | 108069.5                  |
| 3.955            | 109225.2                  |
| 3.501            | 96383.8                   |
| 3.514            | 96497.9                   |
| 3.073            | 83581.2                   |
| 3.089            | 83703.4                   |
| 2.698            | 73966.0                   |
| 2.571            | 71483.3                   |
| 2.395            | 65107.3                   |
| 2.397            | 65132.1                   |
| 2.022            | 56484.7                   |
| 2.080            | 56378.6                   |
| 1.766            | 46463.8                   |
| 1.754            | 46439.4                   |
| 1.424            | 36027.3                   |
| 1.411            | 35372.6                   |
| 1.031            | 22256.5                   |
| 5.795            | 160163.4                  |
| 5.794            | 159525.1                  |
| 5.759            | 159410.2                  |
| 5.174            | 137064.0                  |
| 5.367            | 142331.6                  |
| 5.038            | 130755.4                  |

|       |          |
|-------|----------|
| 5.095 | 151297.1 |
| 5.111 | 151499.5 |
| 4.672 | 127712.6 |
| 4.734 | 128138.9 |
| 4.482 | 117929.8 |
| 4.499 | 117607.6 |
| 4.140 | 102727.8 |
| 4.149 | 103360.1 |
| 3.612 | 86964.6  |
| 3.580 | 86773.1  |
| 3.656 | 87320.4  |
| 3.065 | 72896.1  |
| 3.002 | 72248.9  |
| 3.048 | 72561.7  |
| 2.550 | 60187.0  |
| 2.571 | 60424.5  |
| 2.131 | 50919.6  |
| 2.132 | 50862.4  |
| 0.958 | 19238.4  |
| 1.750 | 41445.3  |
| 1.377 | 30300.0  |
| 1.364 | 29718.1  |
| 0.958 | 19238.4  |
| 5.284 | 160593.7 |
| 5.267 | 160519.1 |
| 4.995 | 145678.9 |
| 4.801 | 137282.6 |
| 4.891 | 141079.3 |
| 4.780 | 133614.7 |
| 4.740 | 133207.9 |
| 4.371 | 119699.4 |
| 4.366 | 119038.3 |
| 4.032 | 105944.4 |
| 4.141 | 107346.9 |
| 3.594 | 93993.6  |
| 3.649 | 94303.2  |
| 3.309 | 83721.0  |
| 3.276 | 82855.1  |
| 2.761 | 70355.9  |
| 2.768 | 70393.6  |
| 2.447 | 60449.6  |
| 2.482 | 60854.3  |
| 1.936 | 49125.5  |
| 1.920 | 48712.4  |

**R134a/DE599**  
(97.7/2.3)  
File: DE5992.DAT

| $\Delta T_c$ (K) | $q''$ (W/m <sup>2</sup> ) |
|------------------|---------------------------|
| 5.895            | 144925.0                  |
| 5.853            | 142233.3                  |
| 5.694            | 128512.6                  |
| 5.815            | 131879.4                  |
| 5.682            | 124398.9                  |
| 5.707            | 126137.8                  |
| 5.476            | 113210.6                  |
| 5.510            | 115216.9                  |
| 5.148            | 99145.7                   |
| 5.157            | 98681.6                   |
| 4.666            | 86168.6                   |
| 4.694            | 85784.6                   |
| 4.148            | 73416.9                   |
| 4.254            | 73710.1                   |
| 3.745            | 63085.6                   |
| 3.771            | 62874.6                   |
| 3.166            | 52119.5                   |
| 3.214            | 52046.6                   |
| 2.594            | 41412.0                   |
| 2.637            | 41348.1                   |
| 1.963            | 28009.6                   |
| 1.999            | 27113.8                   |
| 1.656            | 20001.0                   |
| 1.666            | 19714.1                   |
| 1.189            | 9974.0                    |
| 6.527            | 155390.9                  |
| 6.433            | 155101.6                  |
| 6.236            | 146253.4                  |
| 6.040            | 138232.5                  |
| 6.046            | 135467.5                  |
| 6.041            | 134858.6                  |
| 5.737            | 118639.7                  |
| 5.866            | 123006.5                  |
| 5.529            | 108129.2                  |
| 5.523            | 106770.1                  |
| 5.140            | 95028.8                   |
| 5.259            | 97956.4                   |
| 4.818            | 86380.2                   |
| 4.683            | 83318.7                   |
| 4.506            | 75746.2                   |
| 4.508            | 75727.6                   |
| 4.124            | 67728.7                   |
| 3.988            | 65517.2                   |
| 3.688            | 58745.8                   |
| 7.183            | 142873.2                  |
| 7.205            | 144350.1                  |
| 7.179            | 145316.4                  |
| 7.053            | 140963.3                  |
| 7.013            | 141428.8                  |
| 6.655            | 127738.7                  |
| 6.727            | 128368.4                  |

|       |          |
|-------|----------|
| 6.365 | 115463.3 |
| 6.448 | 115565.5 |
| 6.134 | 103410.9 |
| 6.170 | 100005.7 |
| 5.796 | 91132.7  |
| 5.936 | 93119.4  |
| 5.181 | 79027.5  |
| 5.194 | 78843.6  |
| 4.586 | 67579.6  |
| 4.704 | 68510.6  |
| 4.844 | 69902.4  |
| 4.251 | 60694.9  |
| 4.301 | 60848.4  |
| 3.822 | 53852.7  |
| 3.976 | 55164.2  |
| 3.394 | 47365.8  |
| 3.474 | 47254.6  |
| 2.841 | 38935.5  |
| 2.946 | 39506.2  |
| 2.177 | 29612.4  |
| 2.230 | 29317.6  |
| 1.645 | 20168.8  |
| 1.633 | 19822.7  |
| 5.989 | 145885.3 |
| 5.962 | 147445.9 |
| 5.720 | 134113.5 |
| 5.765 | 133904.4 |
| 5.562 | 121211.2 |
| 5.596 | 120689.1 |
| 5.364 | 108807.8 |
| 5.303 | 106198.4 |
| 5.181 | 98934.5  |
| 5.273 | 101217.1 |
| 4.723 | 80968.2  |
| 4.828 | 81727.4  |
| 4.672 | 74488.1  |
| 4.696 | 75870.3  |
| 4.327 | 65115.3  |
| 4.395 | 65133.4  |
| 4.144 | 57942.4  |
| 4.113 | 57686.2  |
| 3.249 | 44264.4  |
| 3.279 | 43976.4  |
| 2.643 | 35879.3  |
| 2.692 | 35778.3  |
| 2.104 | 26175.1  |
| 5.782 | 151243.8 |
| 5.729 | 152929.6 |
| 5.328 | 130626.7 |
| 6.852 | 153414.5 |
| 6.808 | 153175.4 |
| 6.343 | 133843.2 |
| 6.488 | 136100.6 |
| 6.354 | 128978.2 |
| 6.378 | 128725.1 |
| 6.181 | 118372.1 |
| 6.852 | 153414.5 |
| 6.808 | 153175.4 |
| 6.343 | 133843.2 |
| 6.488 | 136100.6 |
| 6.354 | 128978.2 |
| 6.378 | 128725.1 |
| 6.181 | 118372.1 |
| 6.135 | 114745.3 |
| 6.173 | 113115.6 |
| 6.180 | 110888.0 |
| 5.939 | 98969.8  |
| 5.914 | 96893.8  |
| 5.701 | 85782.1  |
| 5.733 | 86445.7  |
| 5.370 | 74055.4  |
| 5.329 | 74338.4  |
| 4.865 | 64509.4  |
| 4.850 | 63425.1  |
| 4.283 | 53461.6  |
| 4.269 | 53497.5  |
| 3.714 | 44662.9  |
| 3.702 | 44135.6  |
| 2.816 | 33265.8  |
| 5.975 | 140632.9 |
| 5.987 | 143329.6 |
| 5.763 | 131863.1 |
| 5.745 | 131668.0 |
| 5.510 | 119297.7 |
| 5.550 | 119531.6 |
| 5.299 | 111192.8 |
| 5.363 | 111594.4 |
| 4.956 | 95814.2  |
| 4.965 | 95699.1  |
| 4.462 | 83389.5  |
| 4.594 | 86874.6  |
| 3.951 | 72580.9  |
| 3.905 | 71608.1  |
| 3.400 | 59937.8  |
| 3.555 | 61410.1  |
| 3.010 | 50955.5  |
| 3.018 | 50954.3  |
| 2.522 | 42820.3  |
| 5.922 | 143602.1 |
| 5.894 | 144719.2 |
| 5.656 | 133852.1 |
| 5.731 | 135460.2 |
| 5.474 | 121705.0 |

|       |          |
|-------|----------|
| 5.281 | 108941.9 |
| 5.242 | 108025.5 |
| 5.026 | 99236.9  |
| 5.056 | 98785.3  |
| 4.658 | 86338.3  |
| 4.690 | 86646.3  |
| 4.257 | 77194.2  |
| 4.282 | 77422.2  |
| 3.847 | 65990.0  |
| 3.927 | 67231.4  |
| 3.566 | 60075.4  |
| 3.544 | 59285.3  |
| 3.063 | 51494.1  |
| 3.127 | 51441.1  |
| 2.656 | 42768.0  |
| 5.925 | 146327.2 |
| 5.907 | 146568.3 |
| 5.857 | 146381.5 |
| 5.484 | 129680.9 |
| 5.645 | 131181.1 |
| 5.442 | 118700.9 |
| 5.483 | 118439.0 |
| 5.112 | 103559.3 |
| 5.150 | 103218.1 |
| 5.017 | 94102.9  |
| 5.001 | 94024.8  |
| 4.560 | 82292.5  |
| 4.587 | 82168.2  |
| 4.029 | 69937.5  |
| 4.130 | 70710.9  |
| 4.126 | 70781.1  |
| 3.752 | 63203.2  |
| 3.772 | 62948.0  |

**R134a/DE601  
(99.5/0.5)  
File: DE6015.DAT**

| $\Delta T_c$ (K) | $q''$ (W/m <sup>2</sup> ) |
|------------------|---------------------------|
| 5.166            | 163739.9                  |
| 5.113            | 162752.4                  |
| 4.752            | 147901.7                  |
| 4.807            | 150570.7                  |
| 4.301            | 129533.4                  |
| 4.289            | 129897.7                  |
| 3.767            | 110945.8                  |
| 3.739            | 111474.2                  |
| 3.181            | 93715.0                   |
| 3.254            | 95141.8                   |
| 2.894            | 83335.6                   |
| 2.830            | 83386.8                   |
| 2.547            | 74142.4                   |
| 2.478            | 74228.1                   |
| 2.324            | 69418.8                   |
| 2.123            | 71054.7                   |
| 1.800            | 58423.1                   |
| 1.826            | 58380.7                   |
| 1.697            | 55680.3                   |
| 1.689            | 56004.7                   |
| 1.523            | 52105.7                   |
| 5.077            | 159119.6                  |
| 5.060            | 158789.0                  |
| 4.474            | 133312.1                  |
| 4.409            | 131583.3                  |
| 3.537            | 100146.6                  |
| 3.559            | 101176.4                  |
| 3.154            | 89645.5                   |
| 3.146            | 89322.9                   |
| 2.689            | 76522.4                   |
| 2.731            | 77126.1                   |
| 2.474            | 65938.0                   |
| 5.079            | 155492.1                  |
| 5.044            | 155099.3                  |
| 4.532            | 134860.1                  |
| 4.485            | 134426.1                  |
| 3.499            | 96598.9                   |
| 3.513            | 98842.7                   |
| 2.810            | 76148.7                   |
| 2.825            | 77419.4                   |
| 2.524            | 69887.8                   |
| 2.484            | 69897.5                   |
| 2.361            | 65952.0                   |
| 2.409            | 66804.7                   |
| 1.942            | 56483.6                   |
| 1.944            | 56161.1                   |
| 1.800            | 51118.7                   |
| 1.802            | 53037.5                   |
| 1.528            | 47478.3                   |
| 1.540            | 47068.9                   |
| 1.131            | 38698.7                   |
| 1.132            | 38428.4                   |
| 0.846            | 31698.1                   |
| 0.866            | 31532.0                   |
| 0.574            | 23886.9                   |
| 5.018            | 156700.5                  |
| 5.036            | 156333.3                  |
| 4.761            | 145020.5                  |
| 4.651            | 141849.8                  |
| 3.998            | 117161.9                  |
| 4.003            | 117732.7                  |
| 3.503            | 101058.7                  |

|       |          |
|-------|----------|
| 3.505 | 100937.3 |
| 3.031 | 86822.1  |
| 3.113 | 89137.6  |
| 2.626 | 76051.4  |
| 2.637 | 75001.2  |
| 2.363 | 69297.0  |
| 2.333 | 69048.1  |
| 2.119 | 63442.3  |
| 2.165 | 64428.7  |
| 1.862 | 57286.4  |
| 1.869 | 57182.6  |
| 1.714 | 54326.2  |
| 1.695 | 53821.5  |
| 1.628 | 51443.8  |
| 1.631 | 51975.3  |
| 1.416 | 46818.2  |
| 1.425 | 46500.8  |
| 1.013 | 37707.3  |
| 4.949 | 148604.1 |
| 4.928 | 148328.8 |
| 4.398 | 125981.8 |
| 4.423 | 129094.5 |
| 3.714 | 102965.9 |
| 3.684 | 102527.1 |
| 3.171 | 86647.2  |
| 3.156 | 86453.8  |
| 2.872 | 78644.6  |
| 2.888 | 79077.4  |
| 2.709 | 74481.6  |
| 2.703 | 74768.9  |
| 2.543 | 70245.4  |
| 2.635 | 73134.6  |
| 2.506 | 69876.4  |
| 2.491 | 70131.7  |
| 1.950 | 57716.1  |
| 1.961 | 57375.5  |
| 1.868 | 54395.7  |
| 1.858 | 55254.8  |
| 1.895 | 55137.4  |
| 1.775 | 52428.5  |
| 1.294 | 41462.9  |
| 1.235 | 40765.4  |
| 0.543 | 22872.1  |
| 5.115 | 161074.5 |
| 5.019 | 157223.0 |
| 4.687 | 143290.4 |
| 4.695 | 145224.3 |
| 3.699 | 106864.2 |
| 3.682 | 106033.5 |
| 3.093 | 89343.6  |
| 3.152 | 90227.9  |
| 2.785 | 80223.2  |
| 2.786 | 80368.7  |
| 2.439 | 72175.1  |
| 2.418 | 71804.8  |
| 2.266 | 67915.8  |
| 2.331 | 68667.2  |
| 1.871 | 59093.8  |
| 1.865 | 58409.8  |
| 1.686 | 54444.9  |
| 1.700 | 54826.7  |
| 1.534 | 50765.3  |
| 1.555 | 50689.3  |
| 5.058 | 164320.9 |
| 5.057 | 164151.6 |
| 5.004 | 163490.7 |
| 2.397 | 71234.4  |
| 2.401 | 71508.7  |
| 2.397 | 71164.9  |
| 0.496 | 23875.5  |
| 0.518 | 24006.7  |
| 0.531 | 23889.1  |
| 3.474 | 101302.6 |
| 2.354 | 71024.9  |
| 0.568 | 23193.5  |

**R134a/DE601  
(98.7/1.3)  
File: DE6011.DAT**

| $\Delta T_c$ (K) | $q''$ (W/m <sup>2</sup> ) |
|------------------|---------------------------|
| 5.572            | 155909.5                  |
| 5.587            | 155468.8                  |
| 5.126            | 132474.9                  |
| 5.070            | 132588.8                  |
| 4.448            | 109890.0                  |
| 4.078            | 99236.6                   |
| 4.091            | 100215.9                  |
| 3.446            | 84068.2                   |
| 3.396            | 83139.6                   |
| 2.839            | 69850.7                   |
| 2.803            | 69511.6                   |
| 2.619            | 66547.7                   |
| 2.648            | 66623.4                   |
| 2.201            | 57502.1                   |
| 2.190            | 57445.0                   |
| 2.024            | 54146.7                   |
| 1.995            | 53349.9                   |
| 1.608            | 46153.5                   |
| 1.633            | 47191.5                   |
| 5.619            | 161924.9                  |

|       |          |
|-------|----------|
| 5.616 | 161437.1 |
| 5.483 | 150015.1 |
| 5.533 | 150984.0 |
| 5.118 | 129099.1 |
| 5.085 | 130274.5 |
| 4.433 | 105685.5 |
| 4.385 | 104939.3 |
| 3.779 | 88704.2  |
| 3.858 | 90507.9  |
| 3.495 | 80671.1  |
| 3.352 | 77519.1  |
| 2.996 | 68485.6  |
| 2.929 | 68077.6  |
| 2.442 | 57772.5  |
| 2.467 | 58012.8  |
| 2.263 | 55101.0  |
| 2.295 | 55211.7  |
| 1.860 | 47269.5  |
| 1.810 | 46010.8  |
| 0.750 | 21706.2  |
| 5.387 | 162404.1 |
| 5.393 | 161763.4 |
| 5.304 | 158415.9 |
| 5.146 | 152876.7 |
| 5.203 | 156181.2 |
| 5.209 | 156794.1 |
| 4.699 | 134992.7 |
| 4.677 | 134806.4 |
| 4.266 | 118756.0 |
| 4.183 | 115796.6 |
| 3.810 | 103320.2 |
| 3.833 | 104785.5 |
| 3.524 | 94044.8  |
| 3.516 | 94251.8  |
| 2.747 | 72983.8  |
| 2.712 | 71852.1  |
| 2.362 | 64084.9  |
| 2.394 | 63710.7  |
| 2.048 | 57229.1  |
| 5.415 | 165400.7 |
| 5.378 | 166307.7 |
| 4.847 | 144316.8 |
| 4.800 | 143590.6 |
| 4.251 | 123750.2 |
| 4.407 | 127602.0 |
| 3.859 | 108424.2 |
| 3.817 | 107644.1 |
| 3.247 | 89514.5  |
| 3.340 | 90605.5  |
| 2.994 | 82038.0  |
| 2.968 | 81163.5  |
| 2.762 | 75606.1  |
| 2.755 | 75695.2  |
| 1.940 | 57655.1  |
| 1.963 | 57290.1  |
| 1.229 | 39007.2  |
| 1.326 | 38711.1  |
| 1.177 | 33148.2  |
| 1.230 | 32777.4  |
| 0.897 | 25922.1  |
| 0.918 | 25843.0  |
| 0.820 | 22951.5  |
| 5.353 | 152372.3 |
| 5.167 | 152401.1 |
| 4.998 | 147742.0 |
| 4.900 | 145782.1 |
| 4.728 | 139388.2 |
| 4.722 | 139502.9 |
| 4.339 | 124572.5 |
| 4.342 | 123612.8 |
| 4.106 | 115381.1 |
| 4.117 | 117695.5 |
| 3.055 | 83152.7  |
| 3.058 | 82761.9  |
| 2.334 | 62460.2  |
| 2.191 | 61529.4  |
| 1.734 | 50626.2  |
| 1.750 | 51120.7  |
| 1.237 | 42204.2  |
| 1.279 | 42573.5  |
| 1.018 | 35026.9  |
| 1.062 | 34268.6  |
| 0.916 | 29312.5  |
| 5.276 | 156756.9 |
| 5.194 | 156007.4 |
| 5.124 | 153448.0 |
| 4.522 | 130267.0 |
| 4.535 | 130883.9 |
| 3.776 | 104190.5 |
| 3.733 | 103839.3 |
| 3.186 | 88237.3  |
| 3.234 | 89555.8  |
| 2.526 | 71236.1  |
| 2.487 | 70897.4  |
| 2.509 | 70610.4  |
| 2.450 | 69781.3  |
| 1.707 | 54286.3  |
| 1.761 | 55222.0  |
| 1.227 | 43170.6  |
| 1.273 | 42740.6  |
| 0.791 | 28815.7  |
| 0.813 | 28284.8  |
| 0.600 | 22719.5  |

|       |          |
|-------|----------|
| 0.618 | 22570.2  |
| 5.137 | 153160.7 |
| 5.107 | 153708.1 |
| 4.273 | 119691.5 |
| 4.146 | 116486.2 |
| 4.073 | 113923.3 |
| 4.067 | 114954.9 |
| 3.441 | 95118.7  |
| 3.434 | 94917.1  |
| 2.652 | 74937.2  |
| 2.730 | 75036.4  |
| 2.410 | 68612.8  |
| 2.409 | 68354.9  |
| 1.941 | 58358.0  |
| 1.983 | 58230.4  |
| 1.773 | 55152.2  |
| 1.859 | 55766.3  |
| 1.616 | 51578.4  |
| 1.639 | 51702.6  |
| 1.159 | 41577.8  |
| 1.131 | 41056.7  |
| 0.963 | 36108.6  |
| 1.012 | 35906.9  |
| 0.769 | 29232.9  |
| 5.104 | 154705.2 |
| 5.077 | 154863.6 |
| 4.159 | 120180.3 |
| 4.203 | 121720.0 |
| 3.049 | 85538.1  |
| 3.041 | 85292.5  |
| 2.553 | 74684.9  |
| 2.534 | 74149.5  |
| 2.309 | 67421.5  |
| 2.308 | 67728.1  |
| 1.826 | 58427.1  |
| 1.884 | 58520.7  |
| 1.819 | 57524.9  |
| 1.797 | 57832.9  |
| 1.573 | 52837.7  |
| 1.613 | 53402.4  |
| 1.448 | 48401.2  |
| 1.407 | 48031.2  |
| 1.082 | 39429.1  |
| 1.111 | 39544.2  |
| 0.861 | 33013.4  |
| 0.891 | 33011.3  |
| 0.735 | 29386.0  |
| 0.773 | 29346.9  |
| 0.655 | 24836.8  |
| 0.615 | 24724.3  |

**R134a/DE601  
(96.7/3.3)  
File: DE6012.DAT**

| $\Delta T_c$ (K) | $q''$ (W/m <sup>2</sup> ) |
|------------------|---------------------------|
| 5.417            | 159468.8                  |
| 5.428            | 158976.8                  |
| 4.619            | 122919.2                  |
| 4.711            | 126277.6                  |
| 4.000            | 101884.2                  |
| 3.921            | 100751.5                  |
| 3.136            | 78092.4                   |
| 3.050            | 77102.8                   |
| 2.642            | 67064.0                   |
| 2.672            | 68227.5                   |
| 2.166            | 57355.1                   |
| 2.181            | 57606.9                   |
| 1.997            | 53057.8                   |
| 2.053            | 53973.2                   |
| 1.684            | 46657.7                   |
| 1.721            | 46707.9                   |
| 1.325            | 36256.7                   |
| 1.364            | 35198.5                   |
| 0.737            | 22062.2                   |
| 5.890            | 158785.1                  |
| 5.925            | 157368.1                  |
| 5.449            | 137324.9                  |
| 5.313            | 132251.8                  |
| 4.752            | 113150.6                  |
| 4.722            | 113639.3                  |
| 4.296            | 100309.9                  |
| 4.291            | 101402.0                  |
| 3.869            | 89541.8                   |
| 3.787            | 89239.1                   |
| 3.530            | 80500.1                   |
| 3.339            | 78335.7                   |
| 3.060            | 73095.9                   |
| 3.129            | 73478.3                   |
| 3.056            | 71765.9                   |
| 3.054            | 73595.1                   |
| 2.507            | 58819.6                   |
| 2.609            | 58331.2                   |
| 5.649            | 149221.8                  |
| 5.650            | 149063.6                  |
| 5.000            | 122763.7                  |
| 5.047            | 124933.4                  |
| 4.453            | 98302.2                   |
| 4.485            | 97767.9                   |
| 4.048            | 82018.5                   |
| 4.121            | 82729.4                   |
| 3.748            | 72797.3                   |

|       |          |
|-------|----------|
| 3.761 | 72611.9  |
| 3.464 | 64250.0  |
| 5.709 | 148663.7 |
| 5.778 | 150823.9 |
| 5.524 | 136637.5 |
| 5.569 | 136122.3 |
| 4.945 | 112164.6 |
| 4.900 | 111195.9 |
| 4.429 | 94836.6  |
| 4.480 | 94945.1  |
| 4.085 | 82036.2  |
| 4.182 | 82339.2  |
| 3.900 | 72869.2  |
| 3.891 | 72312.3  |
| 3.583 | 65578.0  |
| 3.662 | 67223.3  |
| 3.544 | 63016.0  |
| 3.523 | 63093.1  |
| 3.101 | 50904.6  |
| 3.100 | 51581.5  |
| 3.071 | 52990.6  |
| 2.973 | 49594.8  |
| 2.979 | 49401.9  |
| 2.563 | 41604.4  |
| 5.821 | 163420.1 |
| 5.833 | 162728.4 |
| 5.030 | 129514.5 |
| 4.865 | 123933.8 |
| 4.269 | 102872.5 |
| 4.235 | 102265.5 |
| 3.780 | 88045.4  |
| 3.641 | 85184.2  |
| 3.266 | 73610.3  |
| 3.486 | 76677.7  |
| 3.068 | 66762.6  |
| 3.129 | 67104.4  |
| 2.742 | 54576.1  |
| 2.758 | 53866.2  |
| 2.674 | 51419.9  |
| 2.694 | 51555.8  |
| 2.323 | 44353.6  |
| 2.341 | 44254.9  |
| 1.762 | 34158.7  |
| 1.769 | 33397.9  |
| 0.911 | 20549.2  |
| 5.902 | 160854.0 |
| 5.952 | 160703.4 |
| 5.967 | 161507.9 |
| 5.219 | 127913.4 |
| 5.183 | 127434.3 |
| 4.520 | 104670.4 |
| 4.509 | 103839.2 |
| 3.945 | 87177.7  |
| 4.011 | 88291.5  |
| 3.638 | 79944.2  |
| 3.653 | 80362.6  |
| 3.231 | 69741.5  |
| 3.309 | 70087.3  |
| 3.299 | 70237.4  |
| 3.288 | 70049.9  |
| 2.464 | 48284.9  |
| 2.519 | 47494.9  |
| 0.834 | 19971.2  |
| 0.883 | 19415.2  |
| 5.529 | 163766.8 |
| 5.605 | 163482.9 |
| 5.014 | 122631.8 |
| 4.988 | 123858.8 |
| 4.079 | 90980.9  |
| 4.065 | 90359.6  |
| 3.198 | 69612.2  |
| 3.236 | 70756.8  |
| 2.993 | 65787.7  |
| 3.019 | 65907.5  |
| 3.586 | 72492.5  |
| 2.809 | 60995.0  |
| 2.731 | 58789.5  |
| 2.893 | 58769.7  |
| 2.752 | 57299.0  |
| 3.208 | 64675.3  |
| 2.642 | 54056.1  |
| 2.524 | 52088.2  |
| 2.497 | 49181.4  |
| 2.437 | 49455.5  |
| 1.931 | 38917.6  |
| 1.914 | 38412.5  |
| 1.398 | 30703.8  |
| 1.438 | 30687.4  |
| 1.032 | 23794.9  |
| 1.023 | 23268.6  |

**Pure R134a**  
**File:**  
**R134aTB.DAT**

| $\Delta T$ (K) | $q''$ (W/m <sup>2</sup> ) |
|----------------|---------------------------|
| 2.800          | 72342.3                   |
| 2.801          | 72146.8                   |
| 2.425          | 61146.8                   |
| 2.389          | 61062.6                   |
| 1.986          | 50696.2                   |
| 1.960          | 50566.7                   |

|       |          |
|-------|----------|
| 1.464 | 40914.8  |
| 1.477 | 40603.6  |
| 1.091 | 30275.3  |
| 1.067 | 30157.8  |
| 0.649 | 22083.8  |
| 0.652 | 22104.7  |
| 0.498 | 17301.7  |
| 0.502 | 17370.1  |
| 0.304 | 12578.1  |
| 0.298 | 12615.3  |
| 0.117 | 9457.0   |
| 2.864 | 75779.9  |
| 2.875 | 75290.3  |
| 2.328 | 61549.6  |
| 2.357 | 61533.2  |
| 1.982 | 51276.5  |
| 1.973 | 51059.1  |
| 1.454 | 40504.0  |
| 1.457 | 40652.4  |
| 1.097 | 30818.7  |
| 1.103 | 30763.2  |
| 0.707 | 22438.3  |
| 0.651 | 22504.6  |
| 0.463 | 17437.4  |
| 0.462 | 17493.9  |
| 0.336 | 12798.6  |
| 0.331 | 12684.5  |
| 0.163 | 9603.8   |
| 0.149 | 9581.9   |
| 2.864 | 75779.9  |
| 2.875 | 75290.3  |
| 2.328 | 61549.6  |
| 2.357 | 61533.2  |
| 1.982 | 51276.5  |
| 1.973 | 51059.1  |
| 1.454 | 40504.0  |
| 1.457 | 40652.4  |
| 1.097 | 30818.7  |
| 1.103 | 30763.2  |
| 0.707 | 22438.3  |
| 0.651 | 22504.6  |
| 0.463 | 17437.4  |
| 0.462 | 17493.9  |
| 0.336 | 12798.6  |
| 0.331 | 12684.5  |
| 0.163 | 9603.8   |
| 2.928 | 75405.6  |
| 2.898 | 75429.1  |
| 2.423 | 61830.1  |
| 2.444 | 61916.9  |
| 1.928 | 50319.7  |
| 1.899 | 50010.0  |
| 1.533 | 40284.0  |
| 1.510 | 40644.9  |
| 1.032 | 30657.5  |
| 1.027 | 30543.2  |
| 0.641 | 22235.3  |
| 0.643 | 22103.3  |
| 0.458 | 16985.2  |
| 1.574 | 46385.9  |
| 0.355 | 13077.0  |
| 0.361 | 13142.2  |
| 0.232 | 9569.7   |
| 0.233 | 9552.6   |
| 0.115 | 6802.5   |
| 0.093 | 6523.6   |
| 0.060 | 4125.4   |
| 2.810 | 72290.8  |
| 2.818 | 71843.1  |
| 2.358 | 60788.1  |
| 2.344 | 60560.8  |
| 1.885 | 49334.7  |
| 1.872 | 49383.5  |
| 1.490 | 39331.5  |
| 1.489 | 39349.2  |
| 1.148 | 31083.8  |
| 1.006 | 31383.6  |
| 0.598 | 22325.7  |
| 0.588 | 22303.9  |
| 0.462 | 18003.5  |
| 0.458 | 17966.0  |
| 0.329 | 13336.4  |
| 0.321 | 13313.2  |
| 0.124 | 9686.2   |
| 4.475 | 154635.8 |
| 4.507 | 155450.7 |
| 4.398 | 151230.2 |
| 4.385 | 151129.6 |
| 3.577 | 111236.9 |
| 3.604 | 110785.0 |
| 2.900 | 83003.6  |
| 2.918 | 83408.1  |
| 2.529 | 70750.6  |
| 2.550 | 71352.5  |
| 2.244 | 63782.4  |
| 4.543 | 164871.0 |
| 4.535 | 165181.1 |
| 4.445 | 157867.4 |
| 4.431 | 157746.9 |
| 3.731 | 118679.1 |
| 3.773 | 119225.5 |
| 3.125 | 90130.4  |
| 3.079 | 89460.6  |

|       |          |
|-------|----------|
| 2.595 | 73531.9  |
| 2.603 | 72788.6  |
| 2.344 | 66533.9  |
| 2.261 | 64502.0  |
| 2.251 | 63767.6  |
| 2.228 | 63879.1  |
| 1.636 | 49421.3  |
| 4.169 | 147201.8 |
| 3.520 | 121555.1 |
| 2.709 | 87403.2  |
| 2.260 | 71275.2  |
| 1.944 | 59003.6  |
| 1.208 | 41354.1  |
| 4.033 | 144401.9 |
| 4.242 | 152691.4 |
| 4.236 | 153517.9 |
| 4.190 | 153978.0 |
| 4.229 | 151957.1 |
| 4.167 | 150570.4 |
| 4.289 | 156520.6 |
| 4.309 | 156960.3 |
| 4.251 | 156209.7 |
| 3.988 | 144649.6 |
| 4.074 | 148813.6 |
| 4.099 | 149632.4 |
| 4.237 | 145114.6 |
| 4.383 | 143517.6 |
| 4.059 | 145837.5 |
| 4.141 | 147019.3 |
| 4.661 | 160058.7 |
| 4.633 | 159568.4 |
| 4.395 | 146555.9 |
| 4.353 | 144252.7 |
| 4.073 | 131163.3 |
| 4.089 | 132056.5 |
| 3.801 | 118752.6 |
| 3.792 | 118442.1 |
| 3.427 | 103320.9 |
| 3.475 | 103743.9 |
| 3.238 | 93751.4  |
| 3.192 | 93716.0  |
| 2.742 | 79719.3  |
| 2.864 | 82410.4  |
| 2.526 | 74201.9  |
| 4.692 | 167269.9 |
| 4.717 | 168741.3 |
| 4.704 | 168644.8 |
| 4.523 | 159092.4 |
| 4.505 | 158706.1 |
| 4.234 | 143341.0 |
| 4.266 | 147334.5 |
| 4.279 | 148099.9 |
| 3.997 | 131057.8 |
| 3.961 | 130562.5 |
| 3.954 | 130454.8 |
| 3.531 | 110972.2 |
| 3.612 | 114009.6 |
| 3.609 | 114010.2 |
| 3.297 | 100978.2 |
| 3.319 | 102165.7 |
| 2.896 | 86640.0  |
| 2.906 | 86383.5  |
| 2.919 | 87283.4  |
| 2.431 | 72180.7  |
| 2.403 | 71969.6  |
| 2.422 | 72485.9  |
| 2.042 | 62227.9  |
| 2.056 | 62491.6  |
| 2.038 | 62520.9  |

Table 4 Number of test days and data points

| Fluid (% mass)         | Number of days | Number of data points |
|------------------------|----------------|-----------------------|
| R134a/DE589 (99.5/0.5) | 6              | 149                   |
| R134a/DE589 (99/1)     | 6              | 137                   |
| R134a/DE589 (98/2)     | 6              | 134                   |
| R134a/DE590 (99.5/0.5) | 9              | 163                   |
| R134a/DE590 (98.8/1.2) | 8              | 191                   |
| R134a/DE590 (97.3/2.7) | 12             | 263                   |
| R134a/DE599 (99.5/0.5) | 9              | 190                   |
| R134a/DE599 (98.9/1.1) | 7              | 134                   |
| R134a/DE599 (97.7/2.3) | 9              | 179                   |
| R134a/DE601 (99.5/0.5) | 7              | 133                   |
| R134a/DE601 (98.7/1.3) | 8              | 167                   |
| R134a/DE601 (96.7/3.3) | 7              | 131                   |
| R134a                  | 23             | 173                   |



Table 5 Constants for cubic boiling curve fits for Turbo-BII™-HP

$$\Delta T_s = A_0 + A_1 q'' + A_2 q''^2 + A_3 q''^3$$

$\Delta T_s$  in Kelvin and  $q''$  in  $W/m^2$

| Fluid  | $A_0$      | $A_1$                    | $A_2$                      | $A_3$                      |
|--|------------|--------------------------|----------------------------|----------------------------|
| R134a/DE589 (99.5/0.5) $\Delta T_s \leq 4.8$ K | -0.552305  | $4.40522 \times 10^{-5}$ | $-5.58725 \times 10^{-11}$ | $-8.33712 \times 10^{-17}$ |
| R134a/DE589 (99/1) $\Delta T_s \leq 4.9$ K     | -0.0785764 | $3.18519 \times 10^{-5}$ | $2.91081 \times 10^{-11}$  | $-2.39599 \times 10^{-16}$ |
| R134a/DE589 (98/2) $\Delta T_s \leq 4.4$ K     | -0.0545181 | $4.07832 \times 10^{-5}$ | $-4.07832 \times 10^{-11}$ | $-2.04793 \times 10^{-16}$ |
| R134a/DE590 (99.5/0.5) $\Delta T_s \leq 4.5$ K | -0.382810  | $3.89896 \times 10^{-5}$ | $2.10968 \times 10^{-11}$  | $-4.48145 \times 10^{-16}$ |
| R134a/DE590 (98.8/1.2) $\Delta T_s \leq 5.0$ K | -0.459516  | $5.35886 \times 10^{-5}$ | $-1.50659 \times 10^{-10}$ | $1.65968 \times 10^{-16}$  |
| R134a/DE590 (97.3/2.7) $\Delta T_s \leq 5.0$ K | 0.273636   | $2.53193 \times 10^{-5}$ | $3.83839 \times 10^{-10}$  | $-2.13652 \times 10^{-15}$ |
| R134a/DE599 (99.5/0.5) $\Delta T_s \leq 4.9$ K | 0.384319   | $1.69417 \times 10^{-5}$ | $2.55120 \times 10^{-10}$  | $-1.15269 \times 10^{-15}$ |
| R134a/DE599 (98.9/1.1) $\Delta T_s \leq 5.3$ K | 0.377557   | $2.66641 \times 10^{-5}$ | $1.69317 \times 10^{-10}$  | $-9.03561 \times 10^{-16}$ |
| R134a/DE599 (97.7/2.3) $\Delta T_s \leq 6.4$ K | 0.0441903  | $8.54216 \times 10^{-5}$ | $-3.88627 \times 10^{-10}$ | $6.57693 \times 10^{-16}$  |
| R134a/DE601 (99.5/0.5) $\Delta T_s \leq 5.1$ K | -0.546989  | $4.36860 \times 10^{-5}$ | $4.66413 \times 10^{-12}$  | $-3.67216 \times 10^{-16}$ |
| R134a/DE601 (98.7/1.3) $\Delta T_s \geq 5.4$ K | -0.540402  | $4.52935 \times 10^{-5}$ | $2.49306 \times 10^{-11}$  | $-4.98398 \times 10^{-16}$ |
| R134a/DE601 (96.7/3.3) $\Delta T_s \geq 6.0$ K | -0.444023  | $7.13944 \times 10^{-5}$ | $-3.01331 \times 10^{-10}$ | $6.46025 \times 10^{-16}$  |
| R134a $\Delta T_s \leq 4.5$ K                  | -0.360766  | $5.28759 \times 10^{-5}$ | $-1.88076 \times 10^{-10}$ | $2.81359 \times 10^{-16}$  |

Table 6 Residual standard deviation of  $\Delta T_s$  from the mean

| Fluid                  | $U$ (K) |
|------------------------|---------|
| R134a/DE589 (99.5/0.5) | 0.09    |
| R134a/DE589 (99/1)     | 0.10    |
| R134a/DE589 (98/2)     | 0.10    |
| R134a/DE590 (99.5/0.5) | 0.11    |
| R134a/DE590 (98.8/1.2) | 0.33    |
| R134a/DE590 (97.3/2.7) | 0.64    |
| R134a/DE599 (99.5/0.5) | 0.11    |
| R134a/DE599 (98.9/1.1) | 0.16    |
| R134a/DE599 (97.7/2.3) | 0.40    |
| R134a/DE601 (99.5/0.5) | 0.08    |
| R134a/DE601 (98.7/1.3) | 0.20    |
| R134a/DE601 (96.7/3.3) | 0.28    |
| R134a                  | 0.11    |

Table 7 Average magnitude of 95 % multi-use confidence interval for mean  $T_w - T_s$  (K)

| Fluid                  | $U$ (K) |
|------------------------|---------|
| R134a/DE589 (99.5/0.5) | 0.048   |
| R134a/DE589 (99/1)     | 0.058   |
| R134a/DE589 (98/2)     | 0.056   |
| R134a/DE590 (99.5/0.5) | 0.055   |
| R134a/DE590 (98.8/1.2) | 0.155   |
| R134a/DE590 (97.3/2.7) | 0.252   |
| R134a/DE599 (99.5/0.5) | 0.052   |
| R134a/DE599 (98.9/1.1) | 0.088   |
| R134a/DE599 (97.7/2.3) | 0.192   |
| R134a/DE601 (99.5/0.5) | 0.046   |
| R134a/DE601 (98.7/1.3) | 0.103   |
| R134a/DE601 (96.7/3.3) | 0.157   |
| R134a                  | 0.058   |

Table 8 Average heat flux ratios versus governing parameters

| Lubricant | $\frac{\overline{q''_m}}{q''_p}$ | $x_m$ | $(v_L - v_r)/v_r$<br>@ 313 K | $(T_s - T_c)/T_c$ |
|-----------|----------------------------------|-------|------------------------------|-------------------|
| DE589     | 1.24                             | 0.5   | 151.8                        | 0.0268            |
| DE589     | 1.13                             | 1.0   | 151.8                        | 0.0268            |
| DE589     | 0.96                             | 2.0   | 151.8                        | 0.0268            |
| DE590     | 1.18                             | 0.5   | 176.9                        | 0.146             |
| DE590     | 1.01                             | 1.2   | 176.9                        | 0.146             |
| DE590     | 0.81                             | 2.7   | 176.9                        | 0.146             |
| DE599     | 1.03                             | 0.5   | 31.2                         | 0.268             |
| DE599     | 0.88                             | 1.1   | 31.2                         | 0.268             |
| DE599     | 0.46                             | 2.3   | 31.2                         | 0.268             |
| DE601     | 1.16                             | 0.5   | 1384.4                       | 0.268             |
| DE601     | 1.09                             | 1.3   | 1384.4                       | 0.268             |
| DE601     | 0.75                             | 3.3   | 1384.4                       | 0.268             |

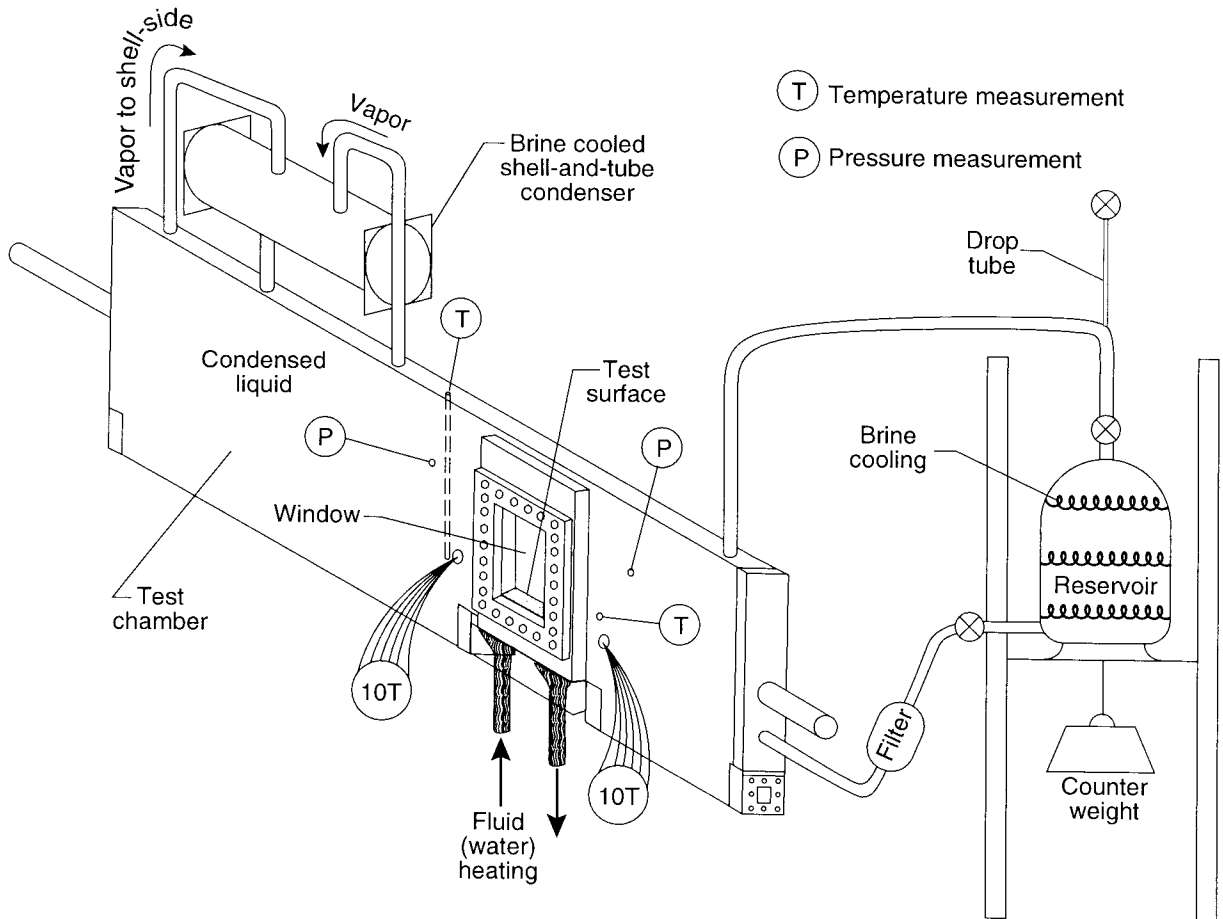


Fig. 1 Schematic of test apparatus

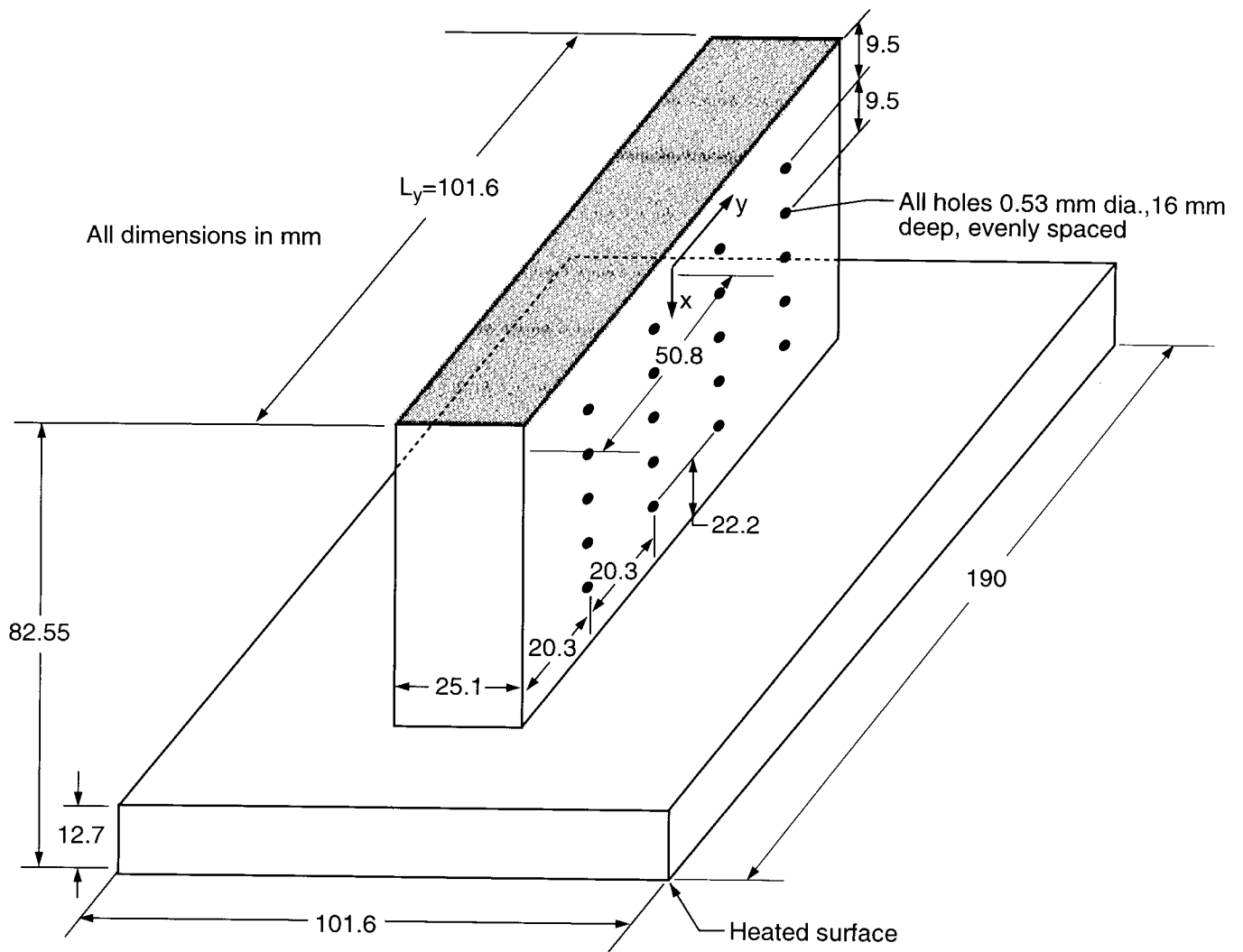
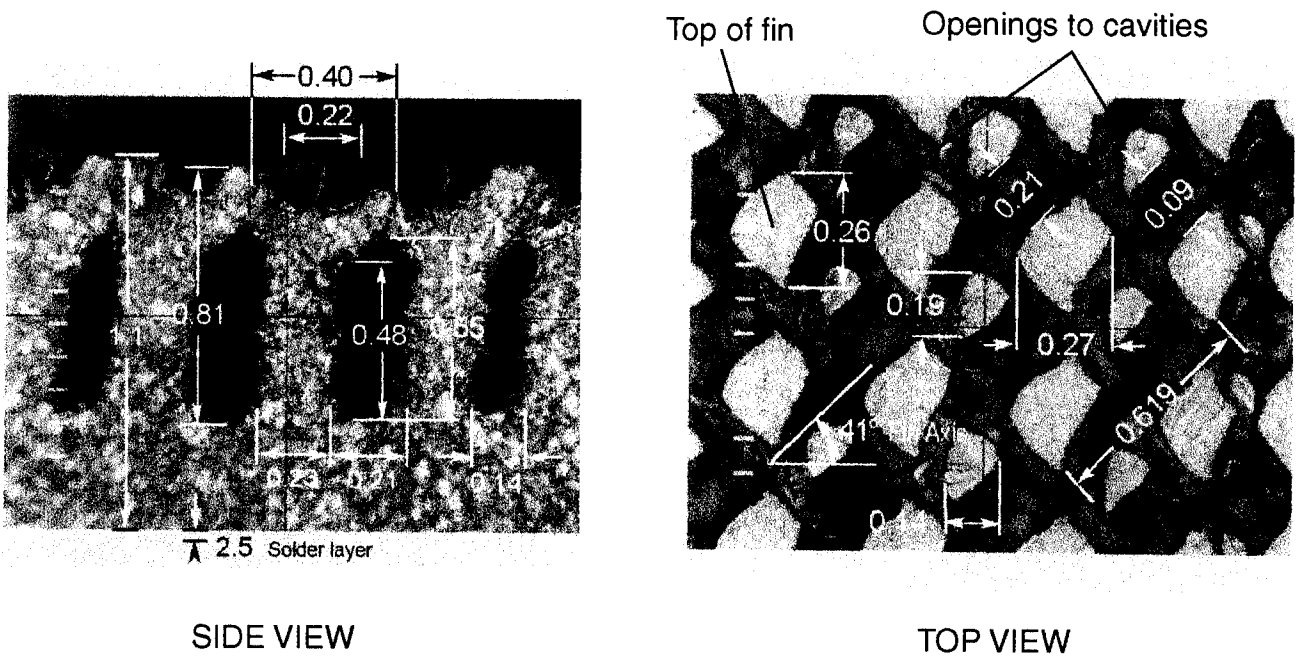


Fig. 2 OFHC copper Turbo-BIII™-HP test plate and thermocouple coordinate system



### TURBO-BII™-HP

Fig. 3 Photograph of Turbo-BII™-HP surface with all dimensions in millimeters

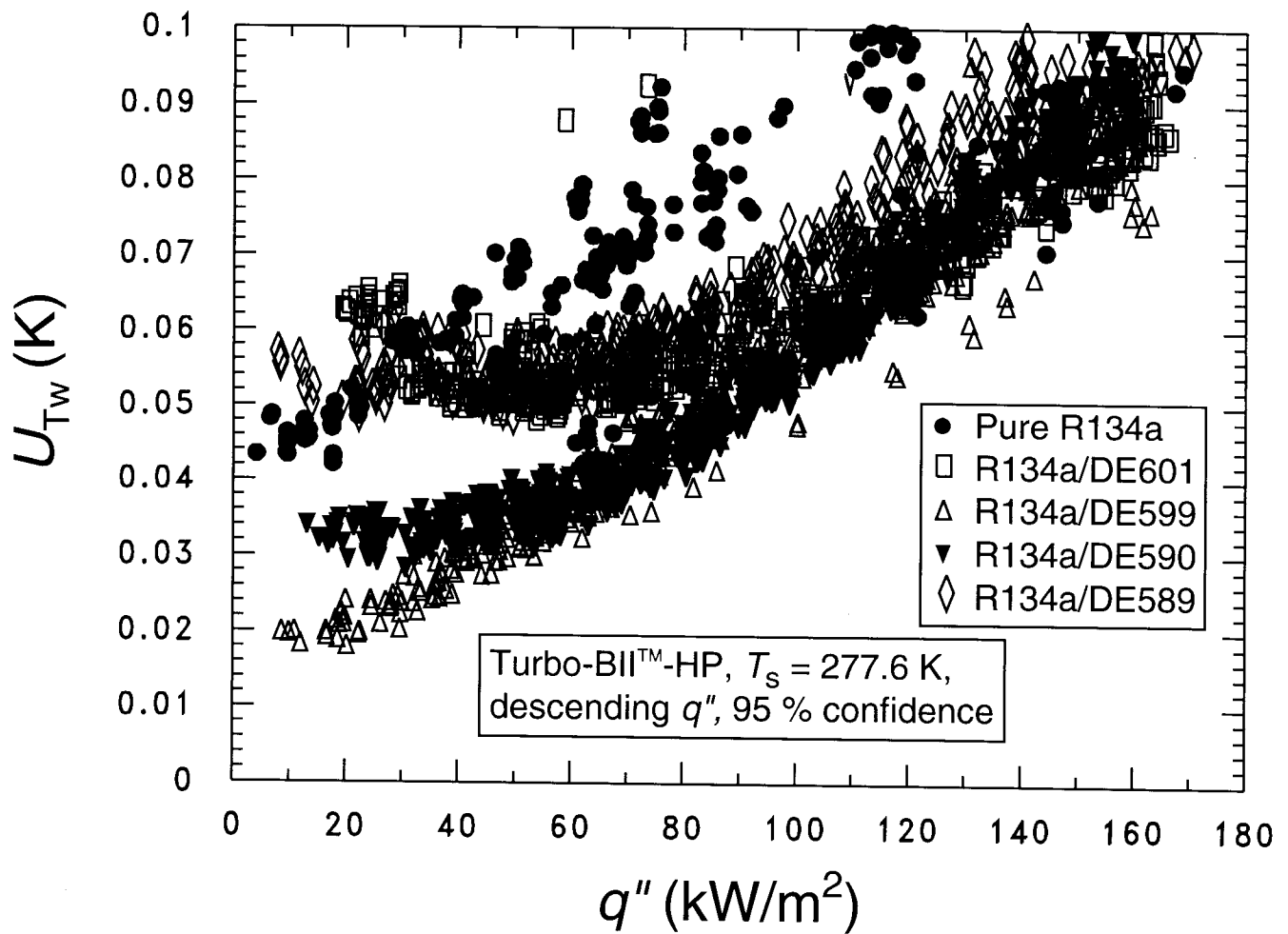


Fig. 4 Uncertainty in the temperature of the surface at the root of the fin for 95 % confidence

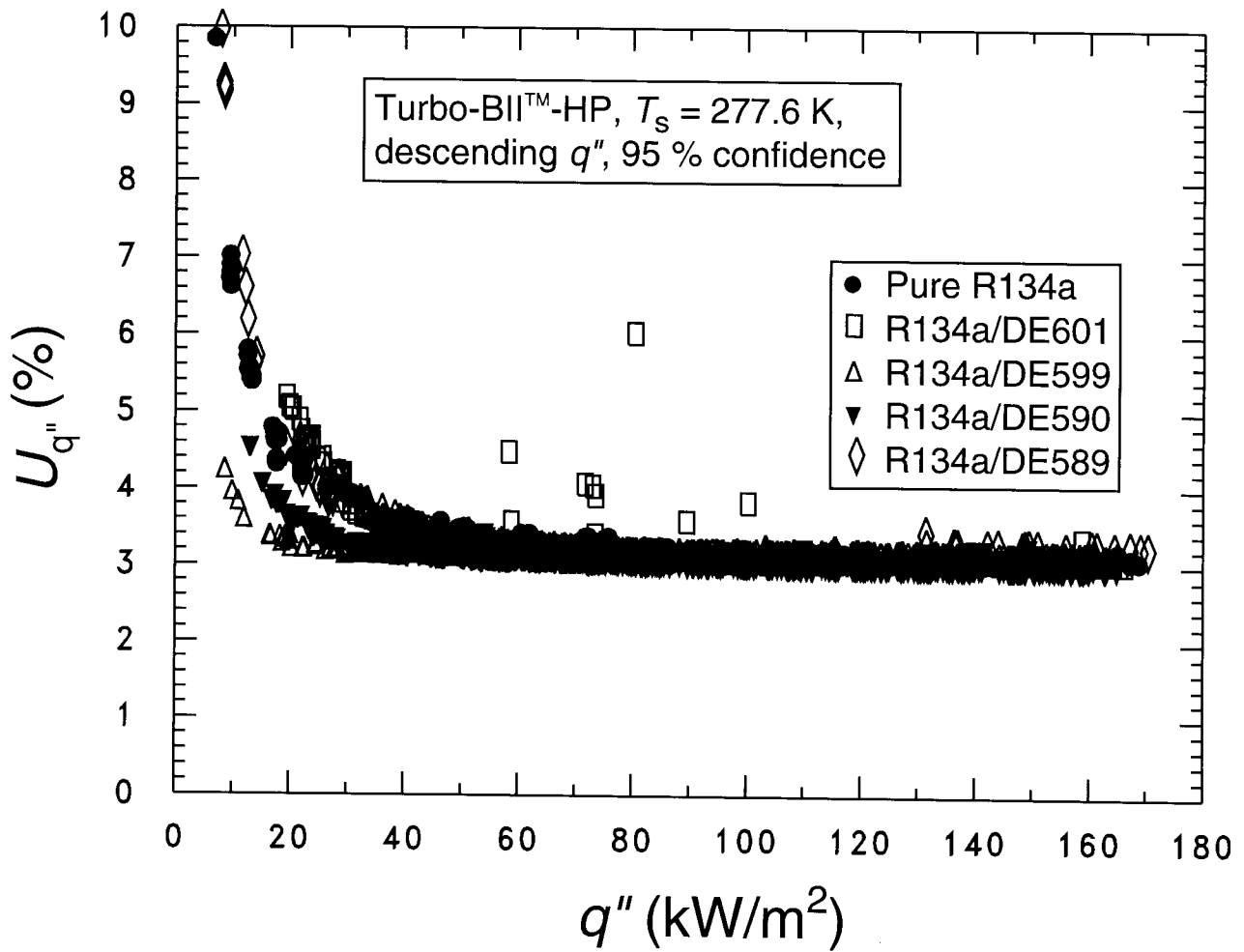


Fig.5 Uncertainty in the heat flux at the root of the fin for 95 % confidence



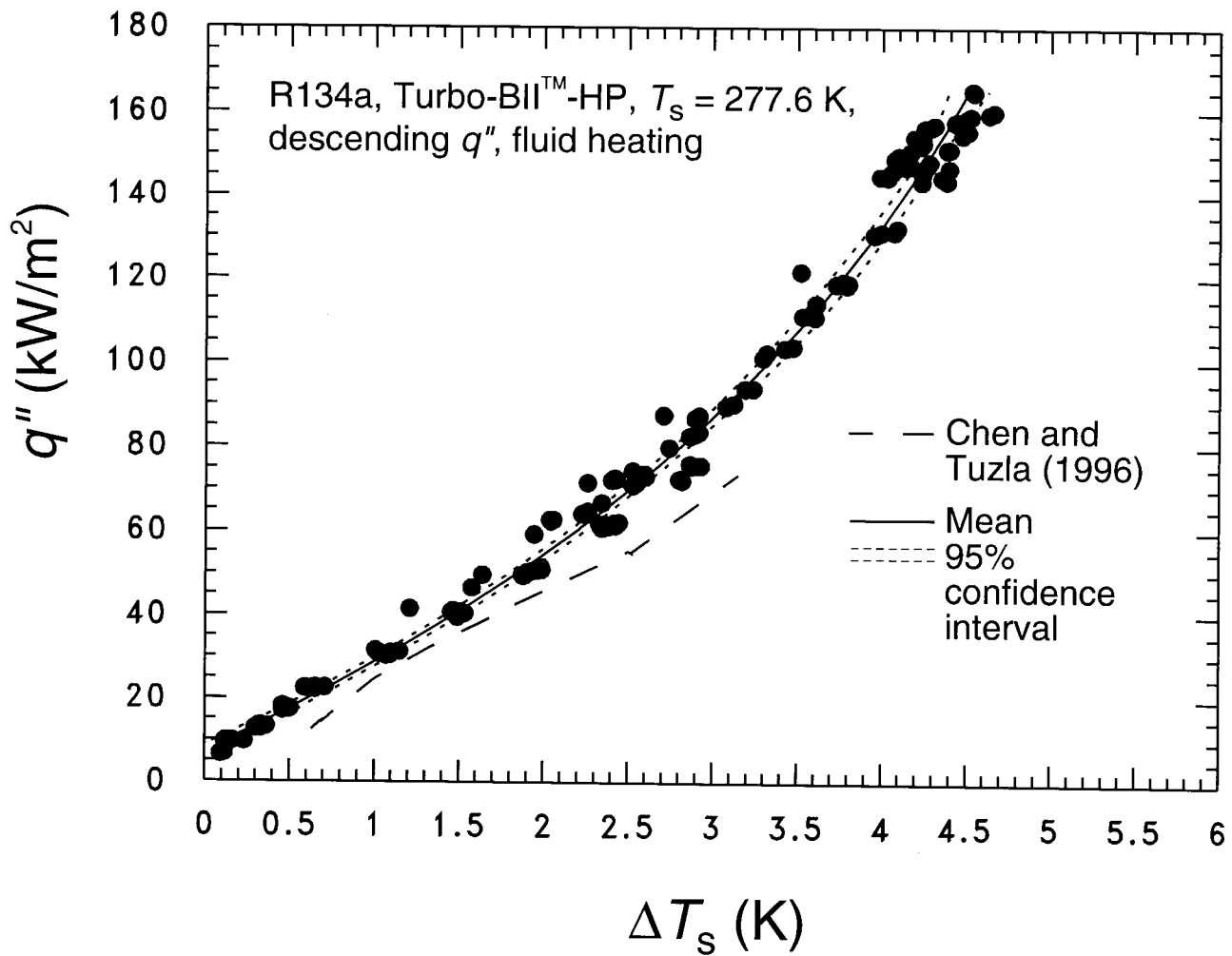


Fig. 6 Pure R134a boiling curve for Turbo-BII™-HP

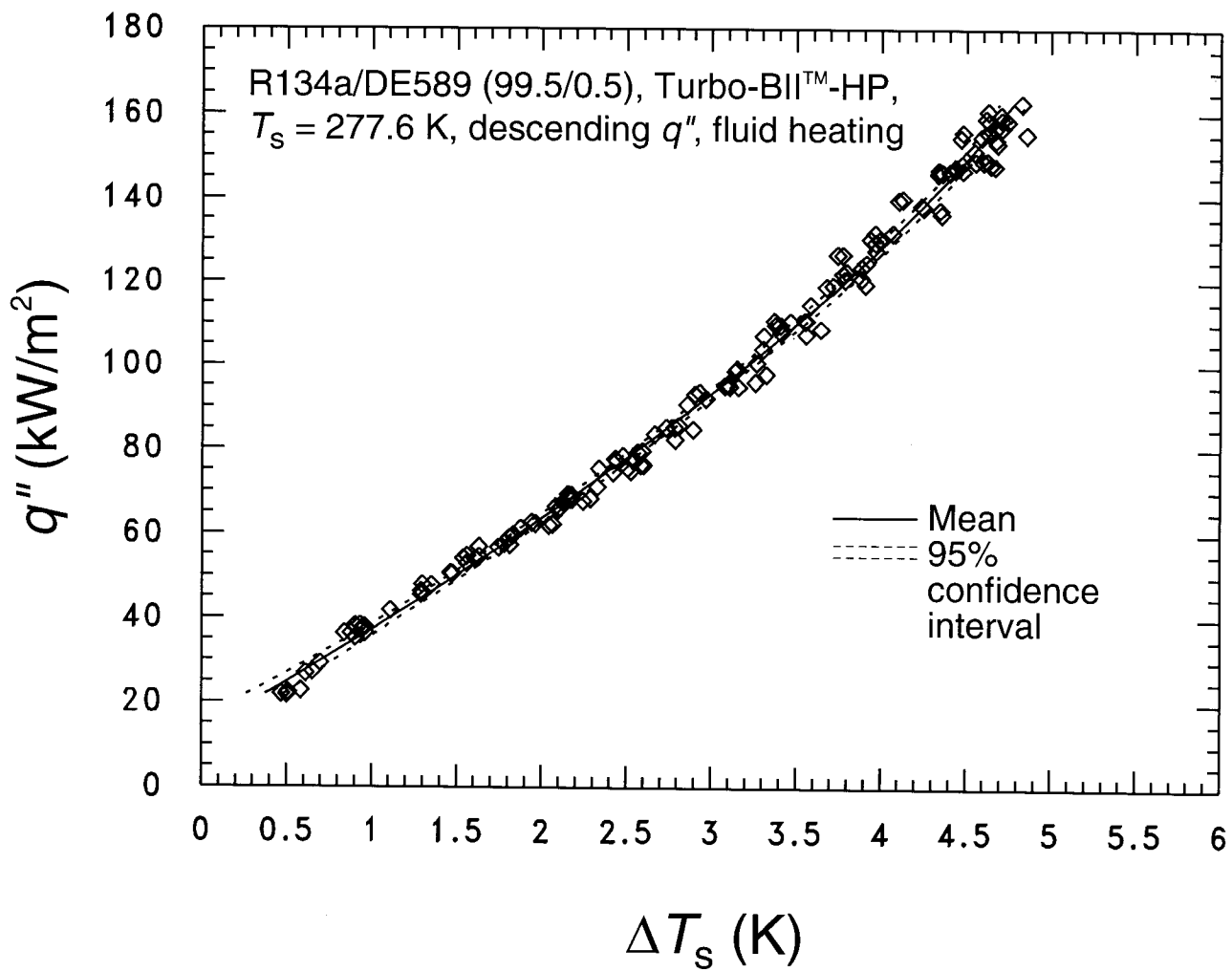


Fig. 7 R134a/DE589 (99.5/0.5) boiling curve for Turbo-BII™-HP

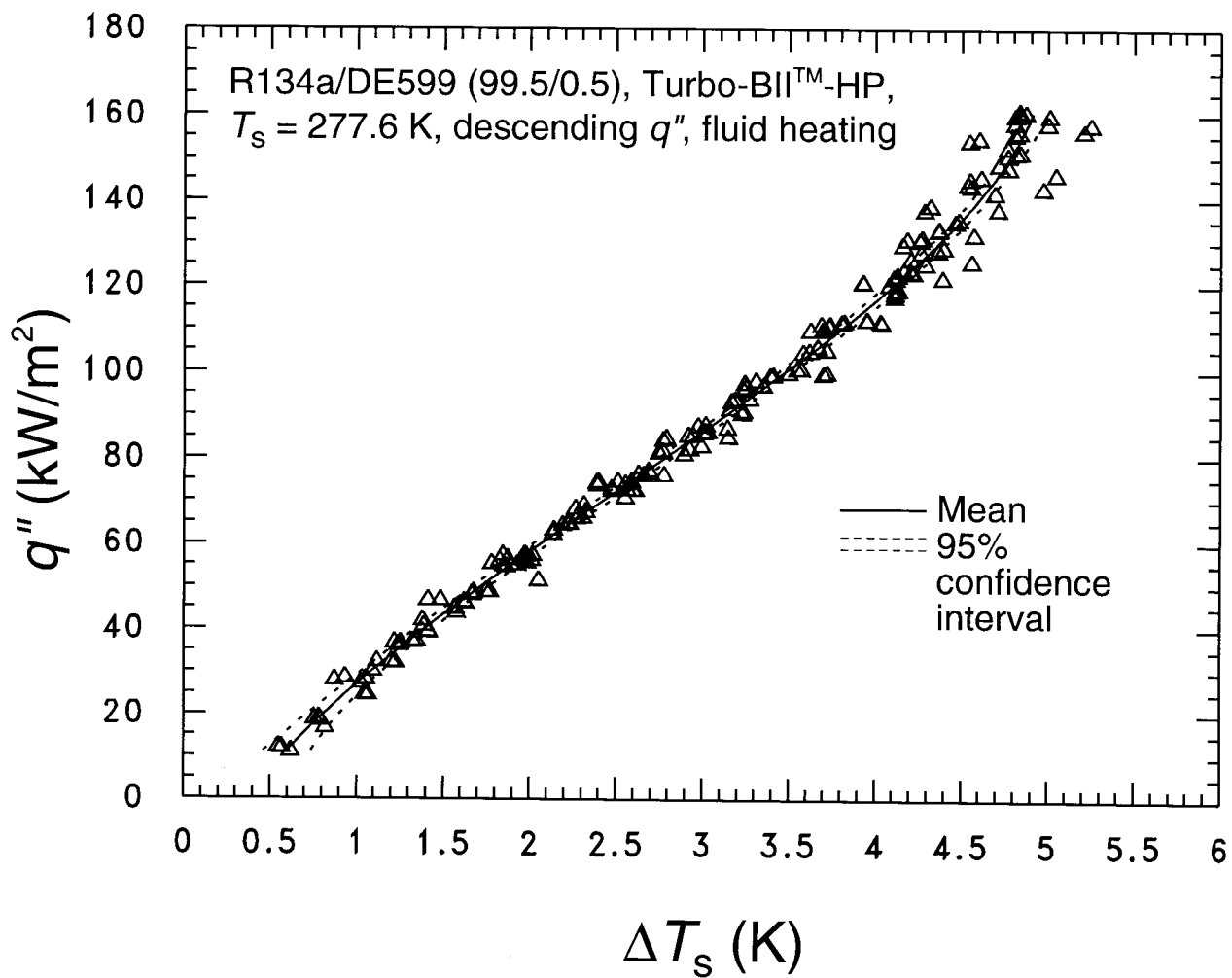


Fig. 8 R134a/DE599 (99.5/0.5) boiling curve for Turbo-BII™-HP

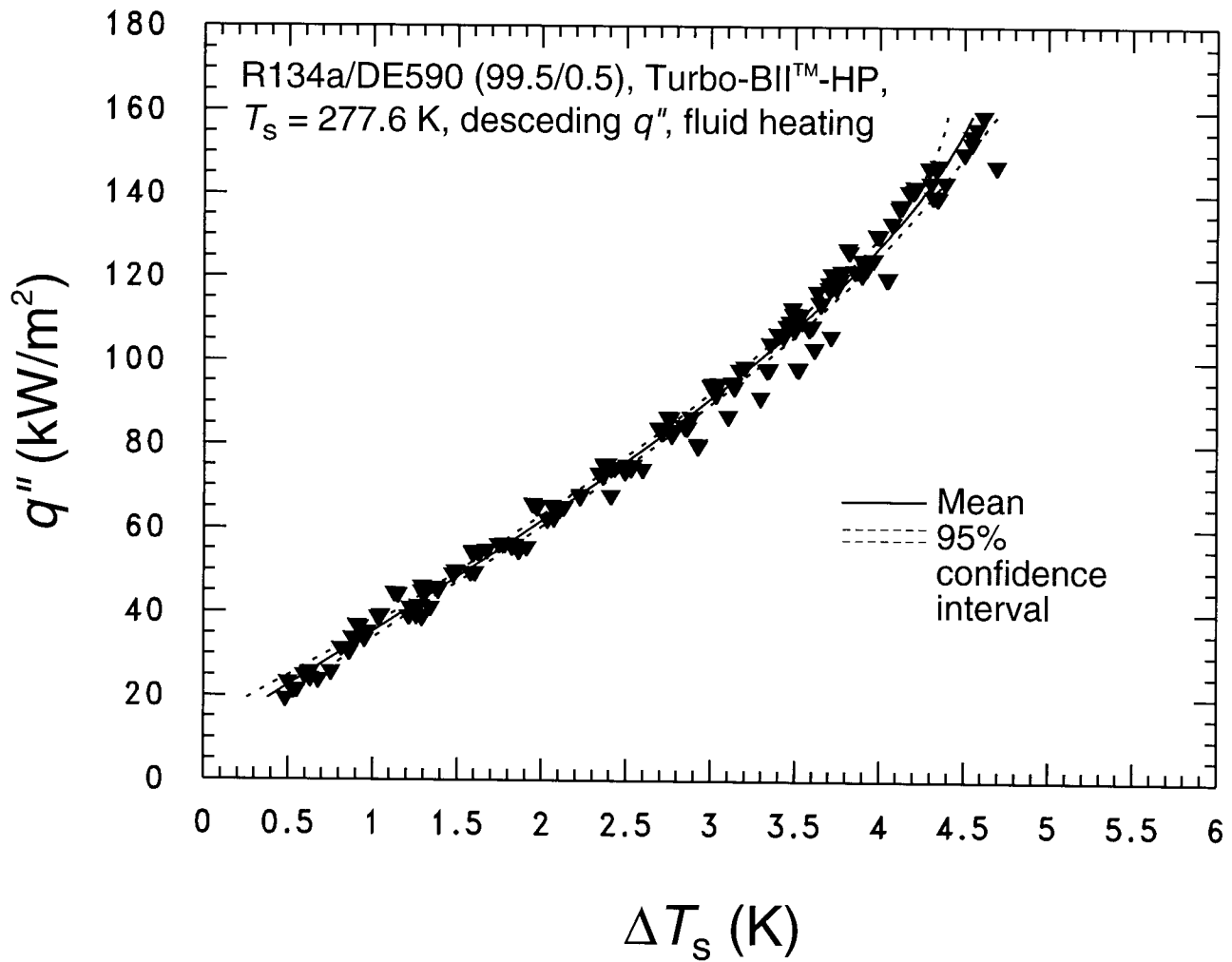


Fig. 9 R134a/DE590 (99.5/0.5) boiling curve for Turbo-BII™-HP

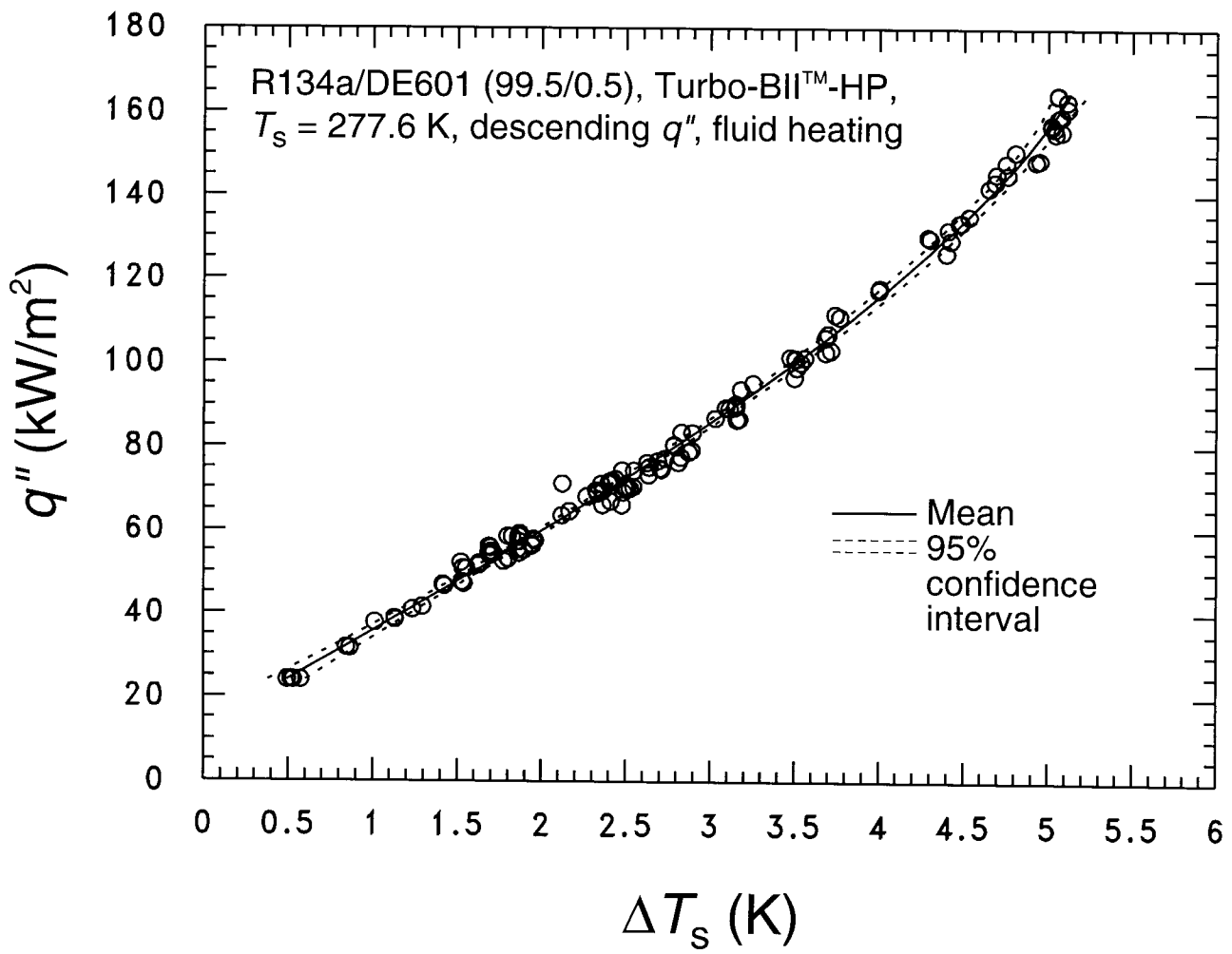


Fig. 10 R134a/DE601 (99.5/0.5) boiling curve for Turbo-BII™-HP

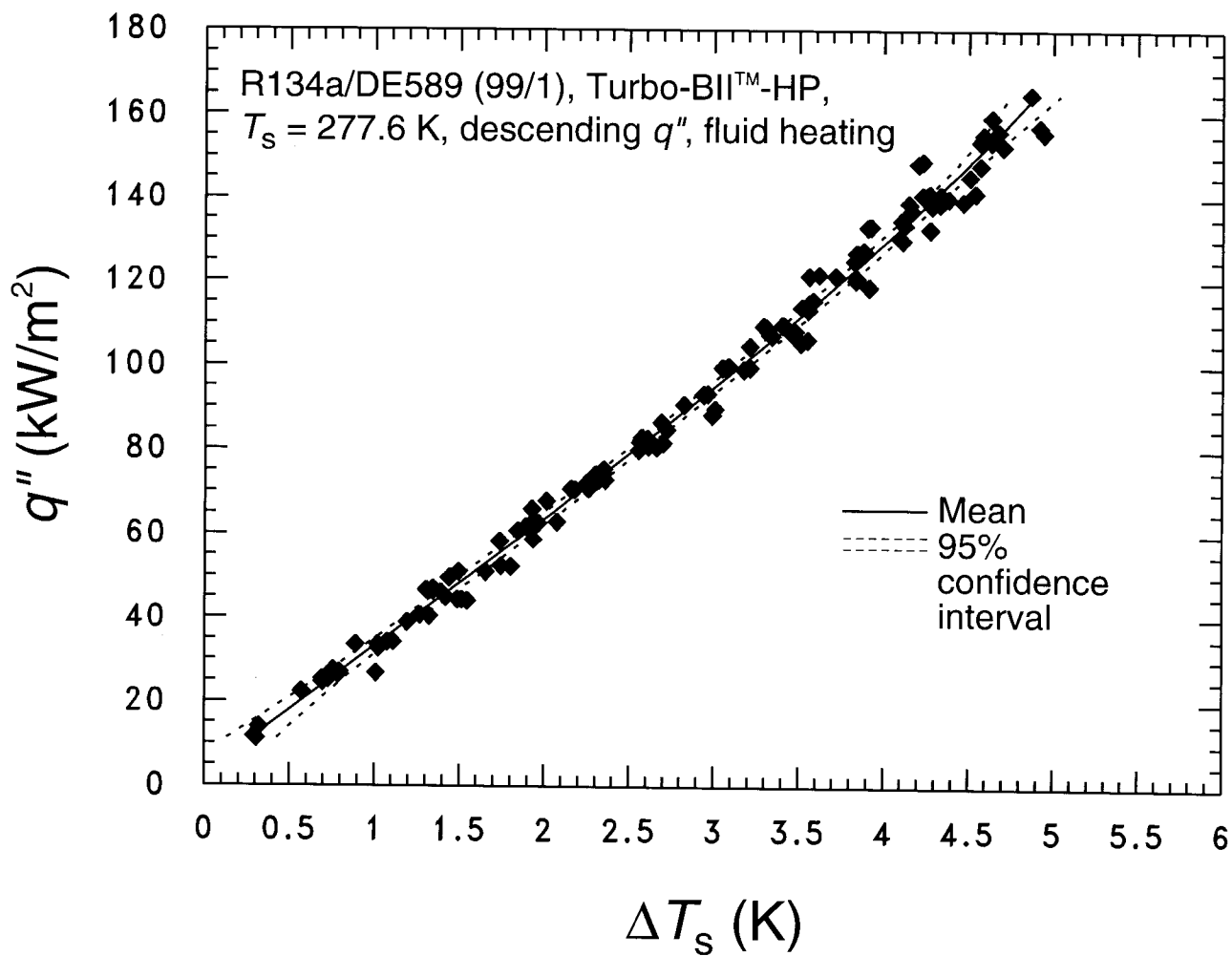


Fig. 11 R134a/DE589 (99/1) boiling curve for Turbo-BII™-HP

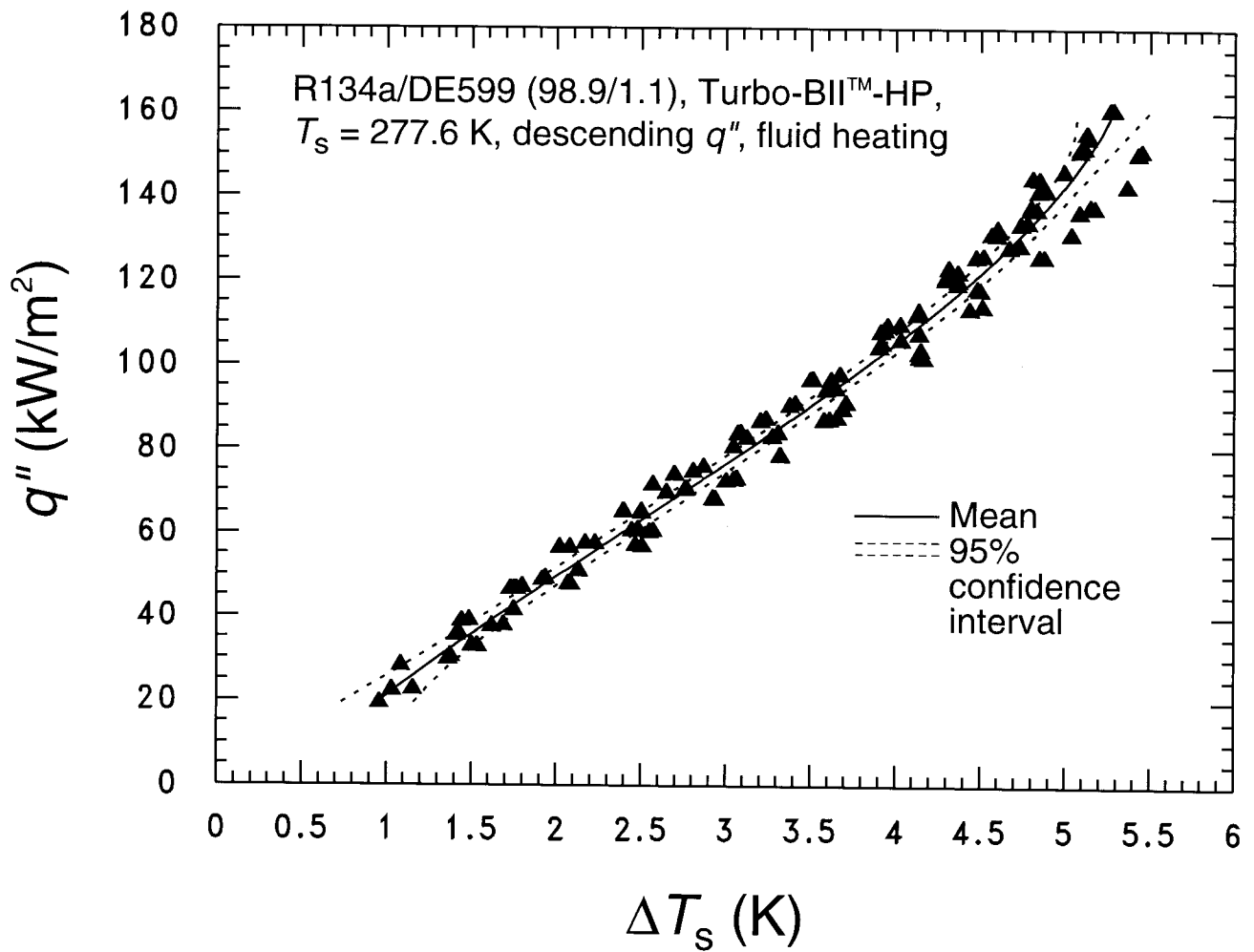


Fig. 12 R134a/DE599 (98.9/1.1) boiling curve for Turbo-BII™-HP

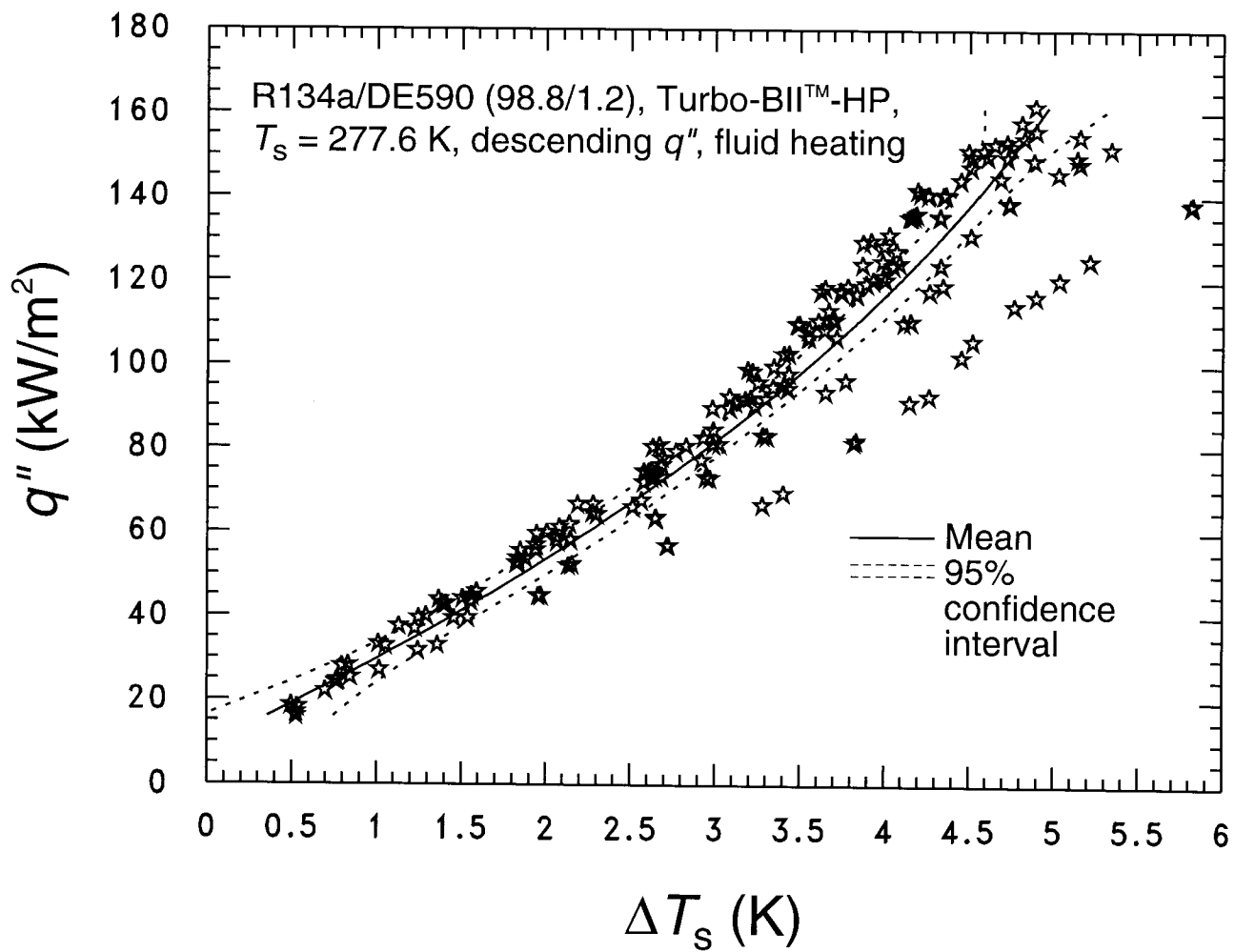


Fig. 13 R134a/DE590 (98.8/1.2) boiling curve for Turbo-BII™-HP



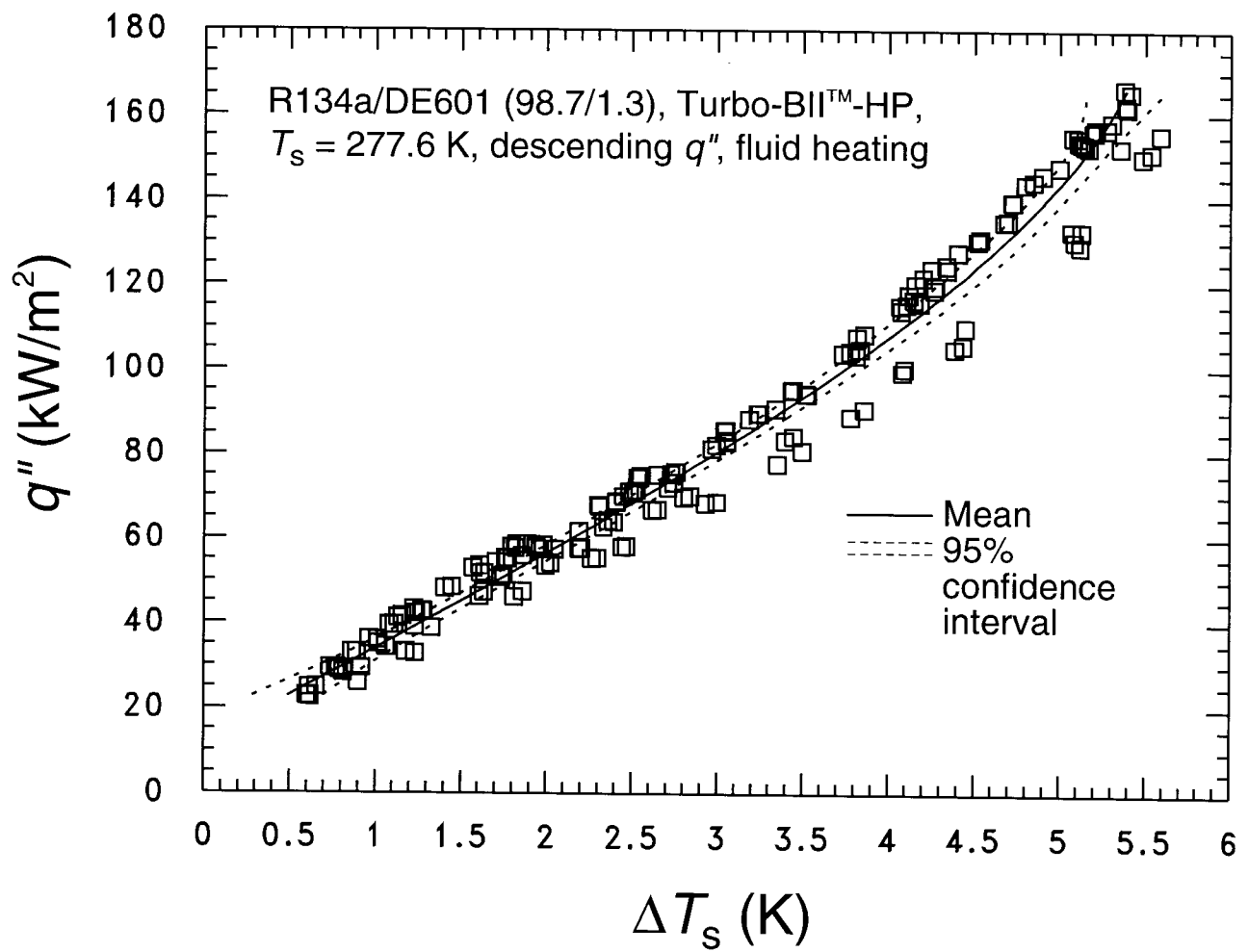


Fig. 14 R134a/DE601 (98.7/1.3) boiling curve for Turbo-BII™-HP

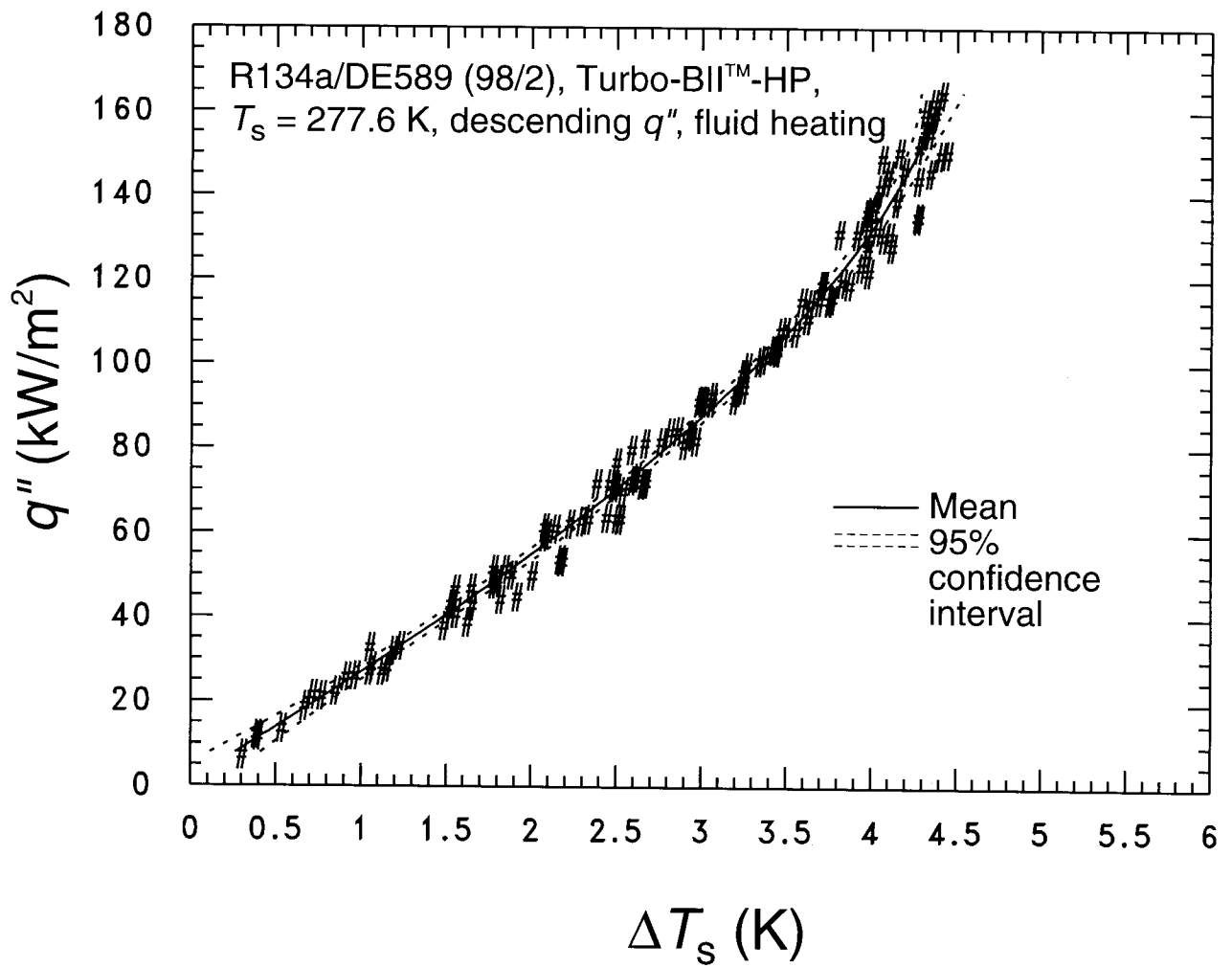


Fig. 15 R134a/DE589 (98/2) boiling curve for Turbo-BII™-HP

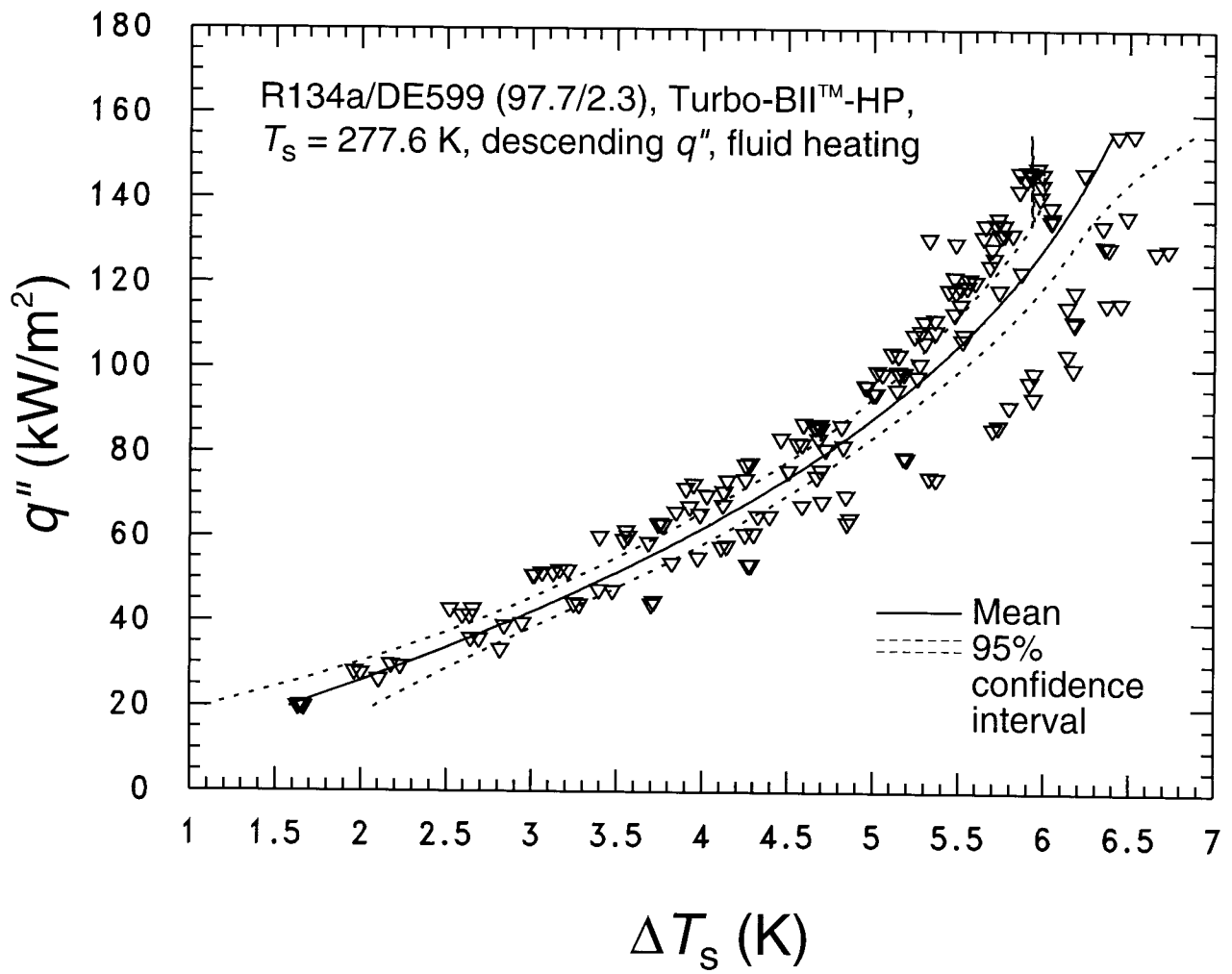


Fig. 16 R134a/DE599 (97.7/2.3) boiling curve for Turbo-BII™-HP

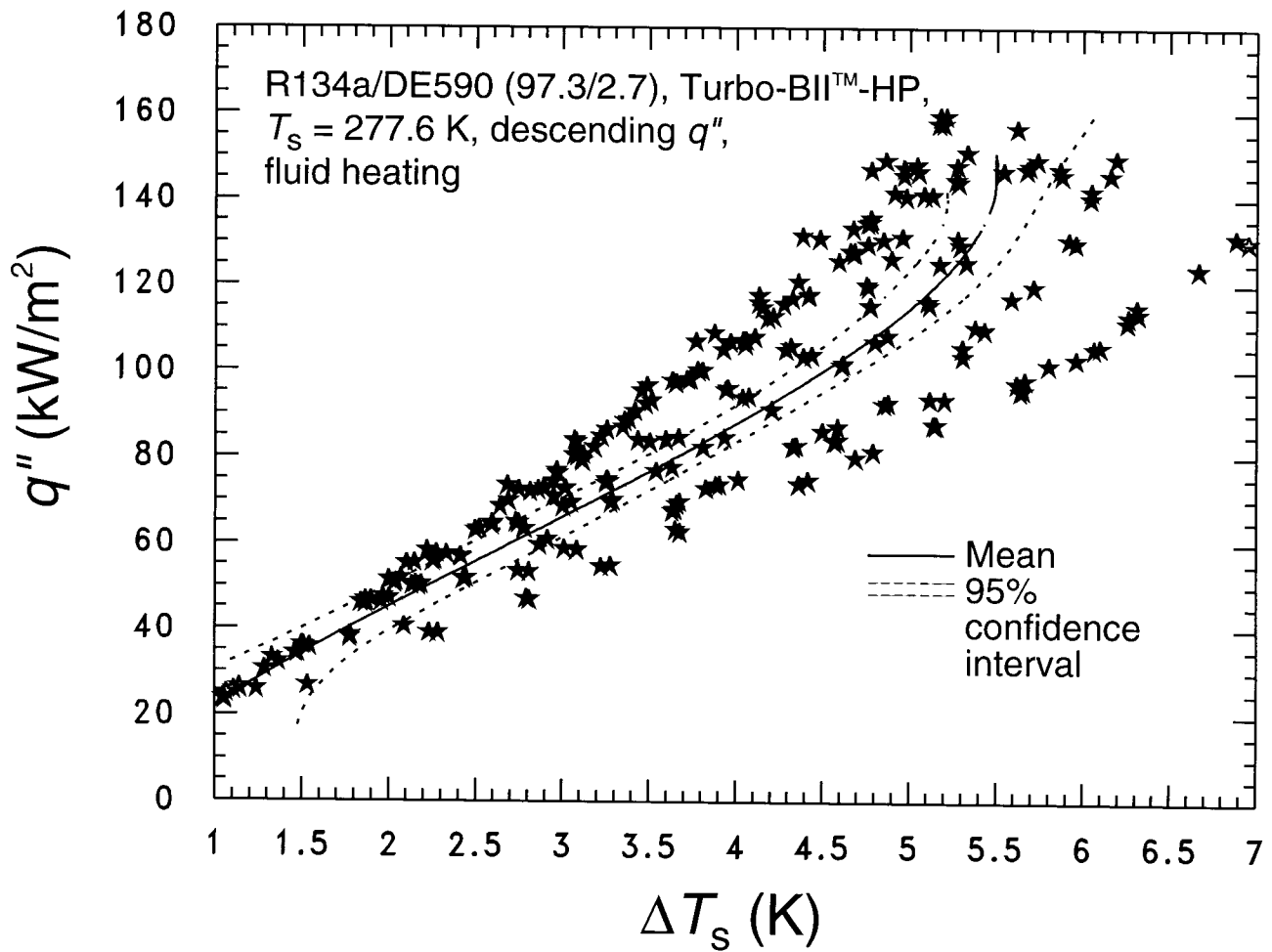


Fig. 17 R134a/DE590 (97.3/2.7) boiling curve for Turbo-BII™-HP

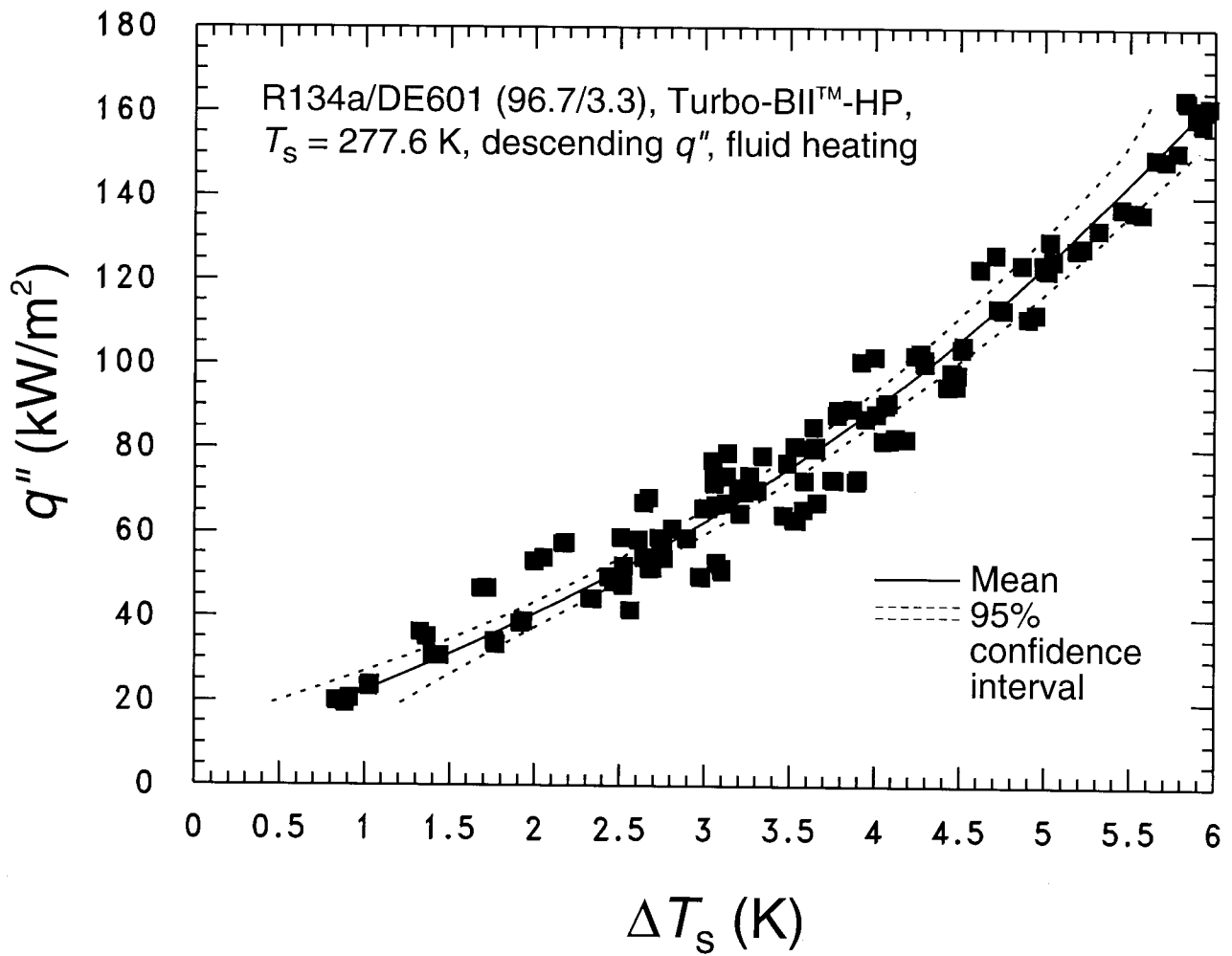


Fig. 18 R134a/DE601 (96.7/3.3) boiling curve for Turbo-BII™-HP

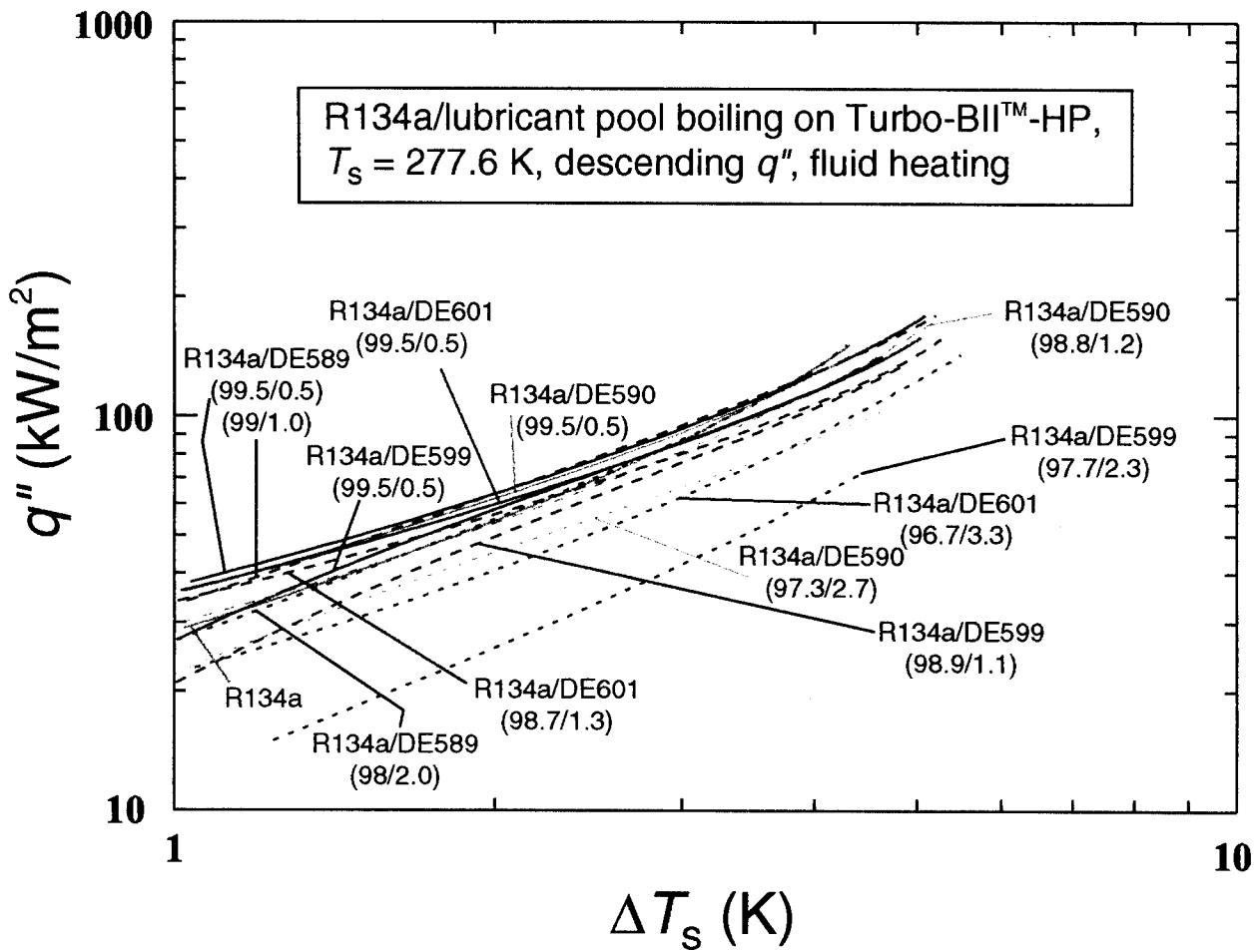


Fig. 19 Pool boiling curves for R134a and twelve R134a/lubricant mixtures on Turbo-BII™-HP

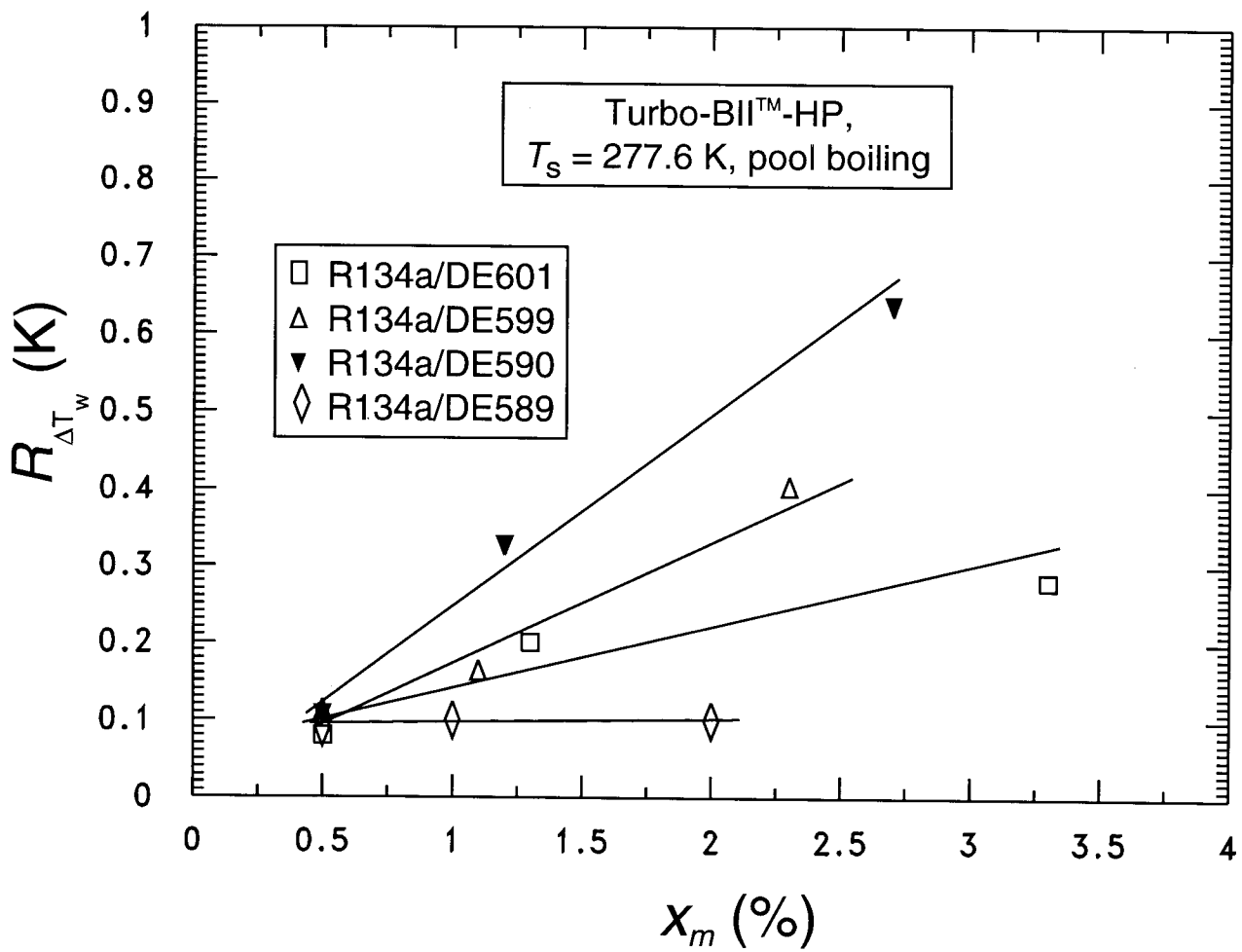


Fig. 20 Effect of lubricant mass fraction on residual standard deviation of cubic fit

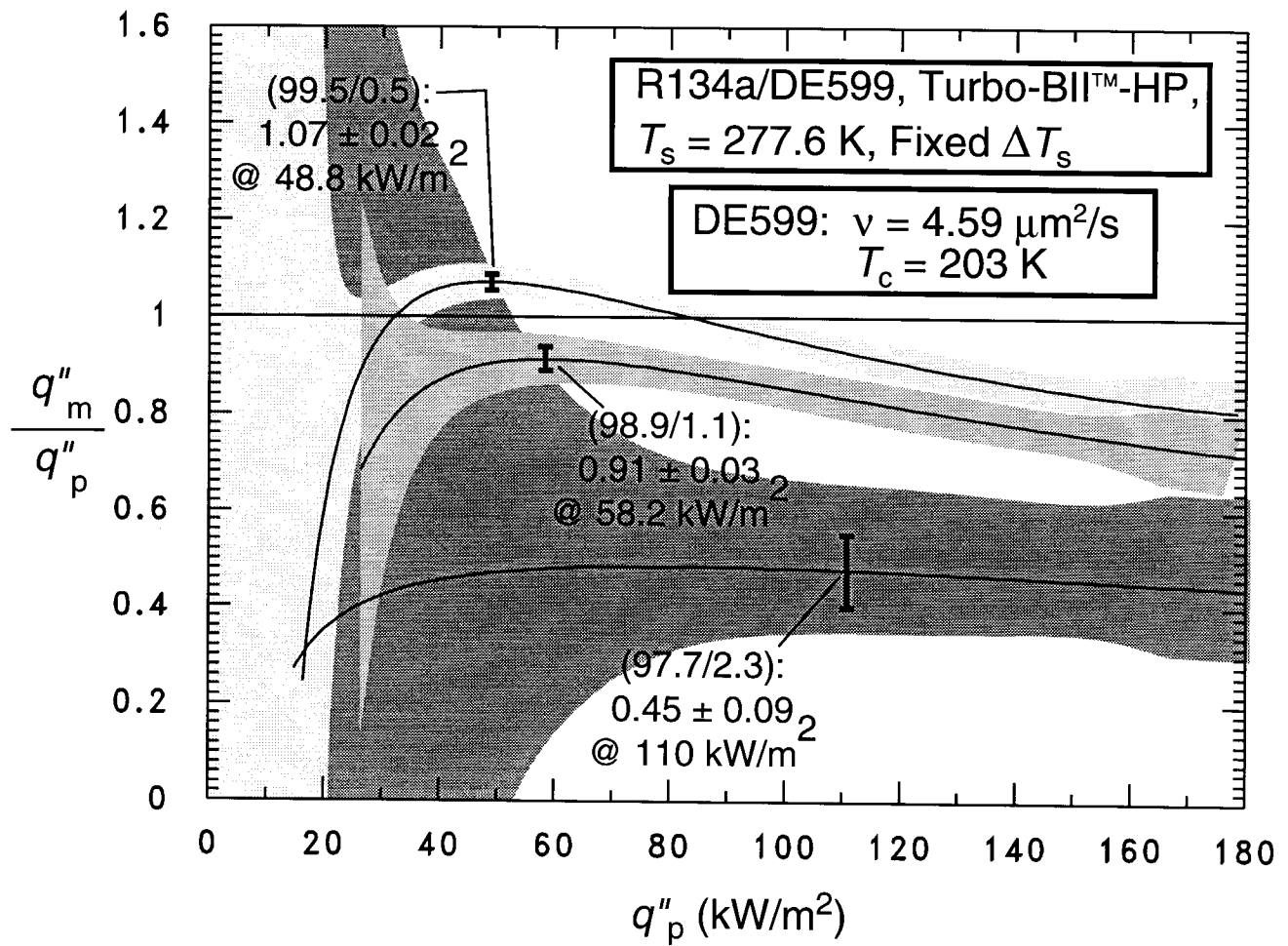


Fig. 21 R134a/DE599 mixtures heat flux relative to that of pure R134a



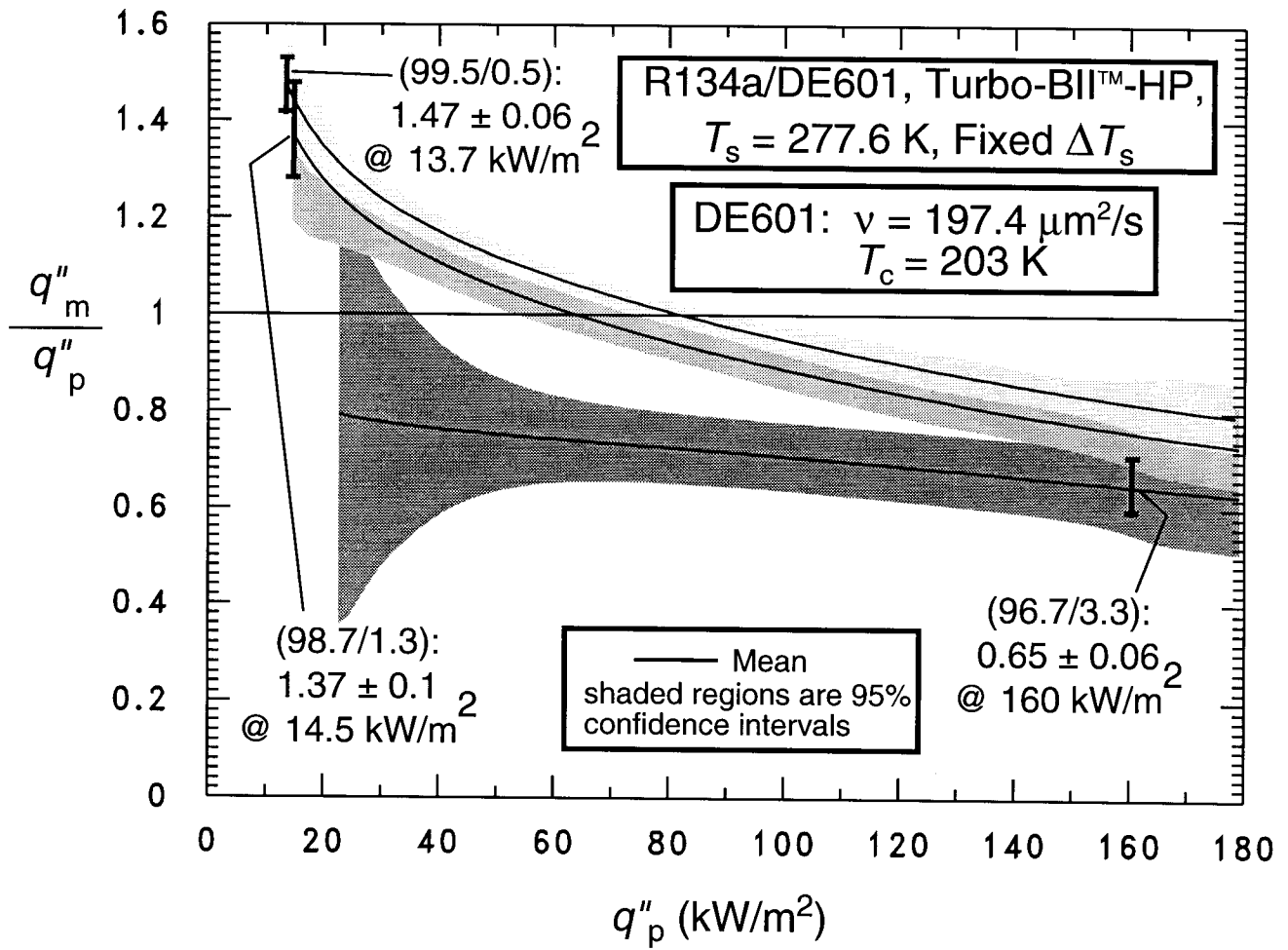


Fig. 22 R134a/DE601 mixtures heat flux relative to that of pure R134a

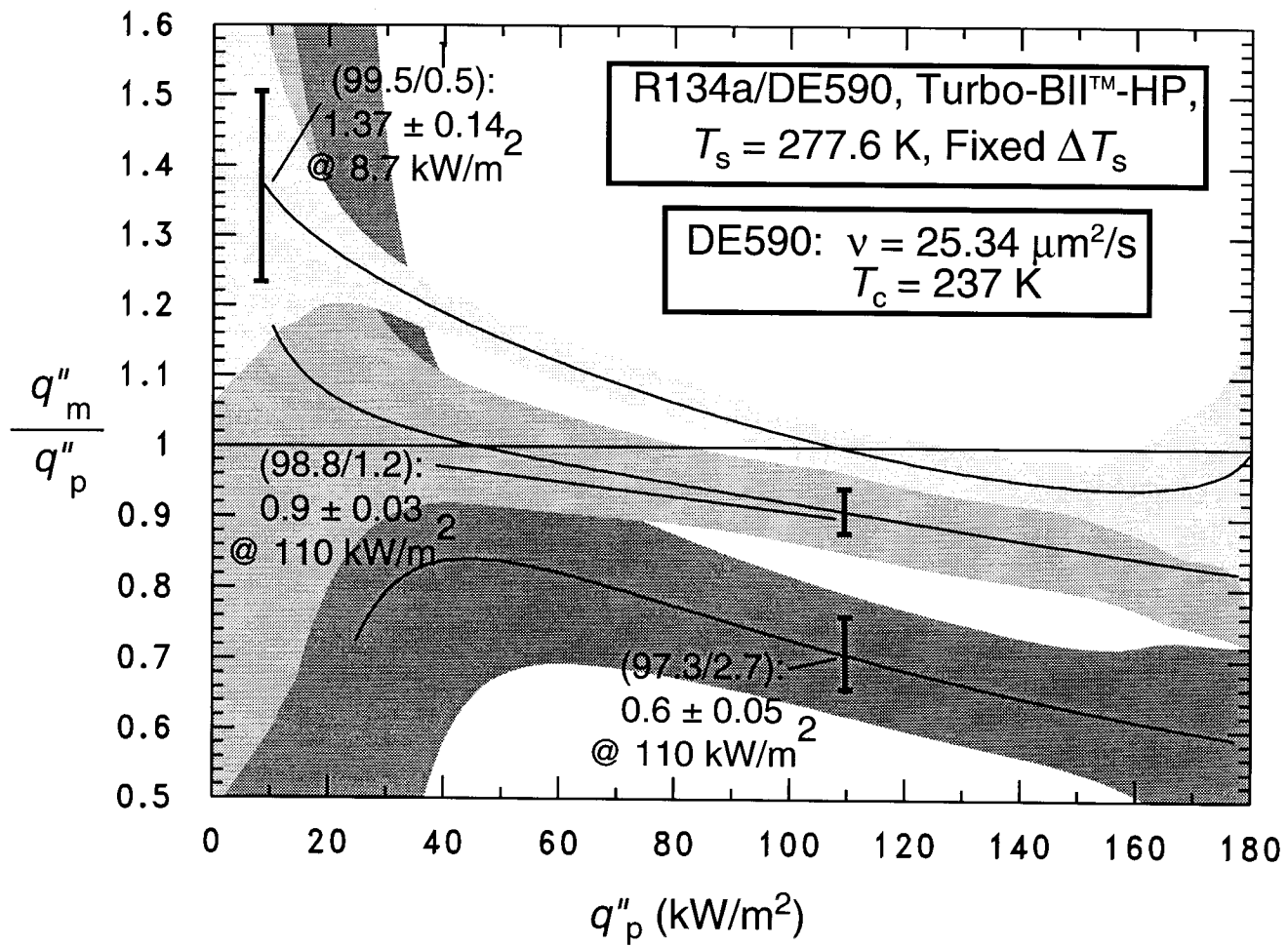


Fig. 23 R134a/DE590 mixtures heat flux relative to that of pure R134a

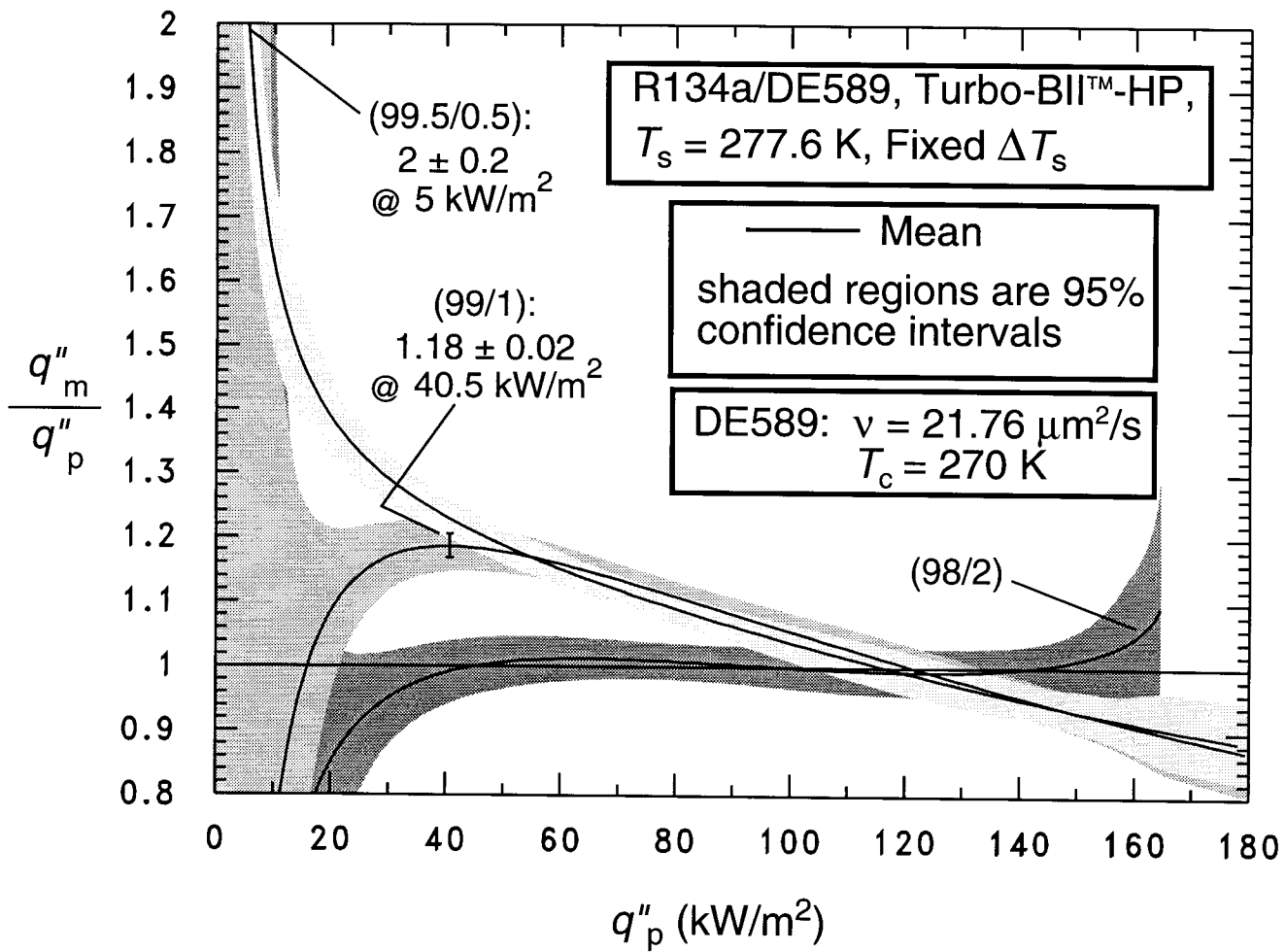


Fig. 24 R134a/DE589 mixtures heat flux relative to that of pure R134a

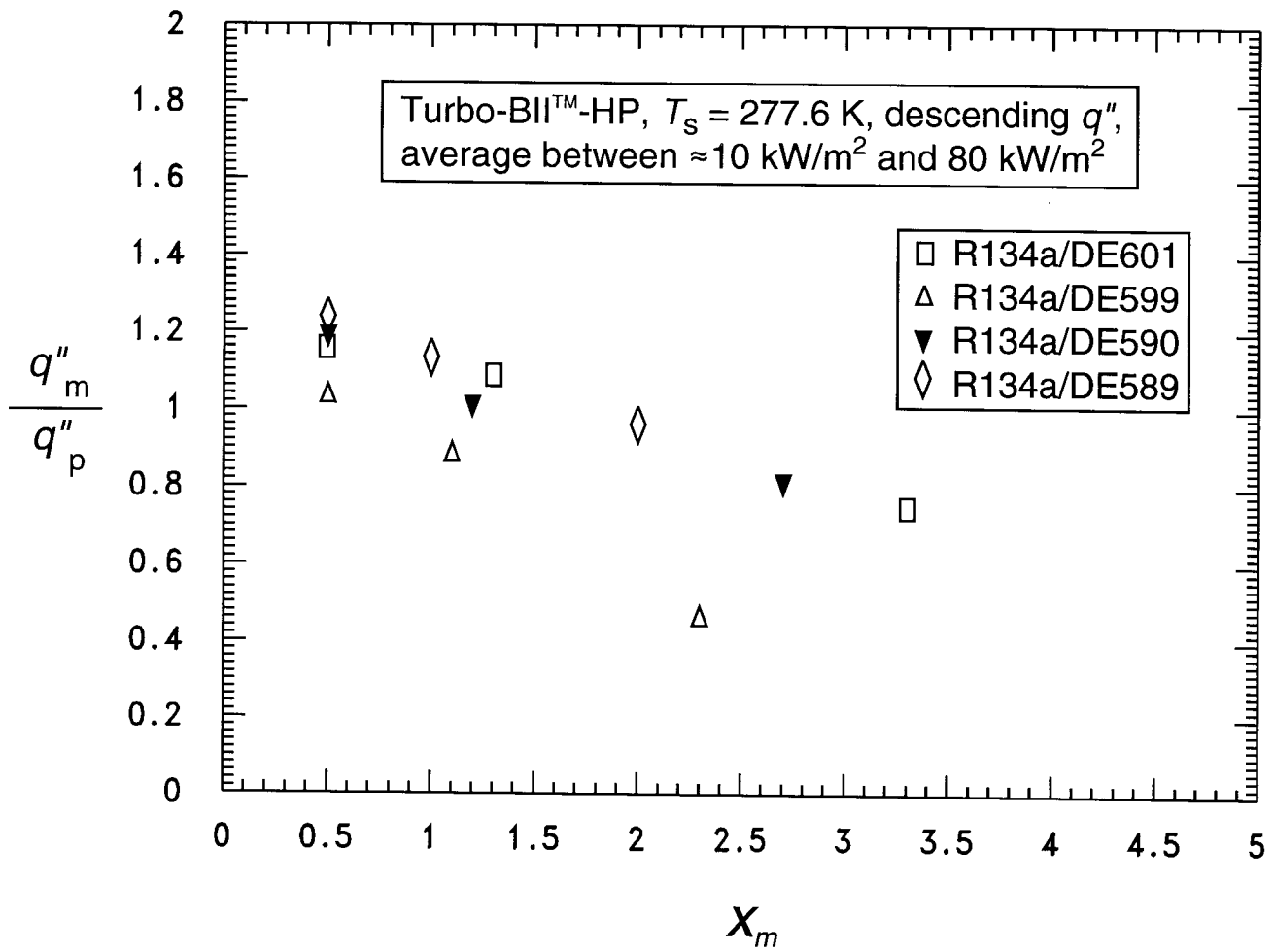


Fig. 25 Influence of lubricant mass fraction on R134a/lubricant pool boiling

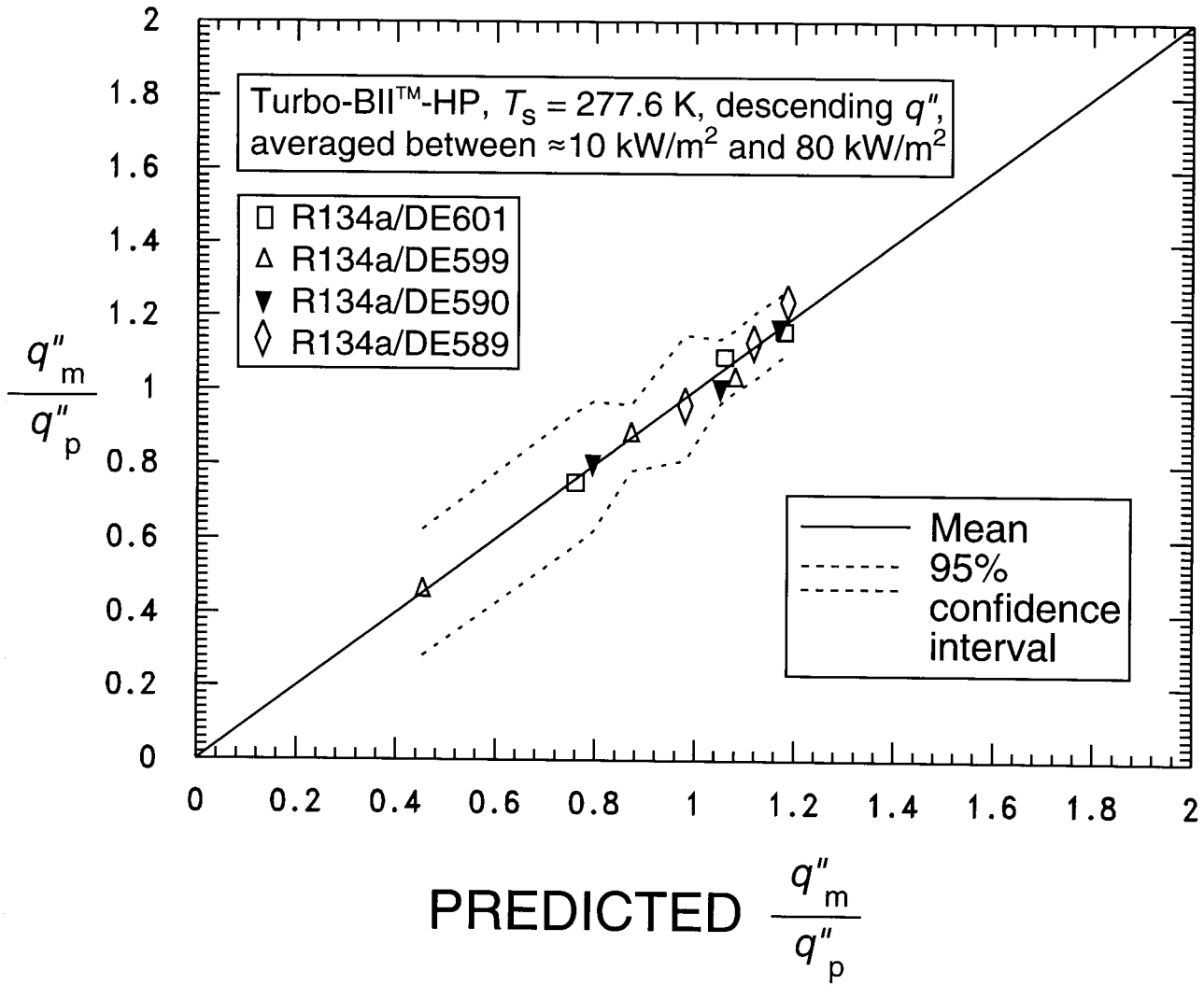


Fig. 26 Comparison of measured heat flux ratio to that predicted by Eq. 5

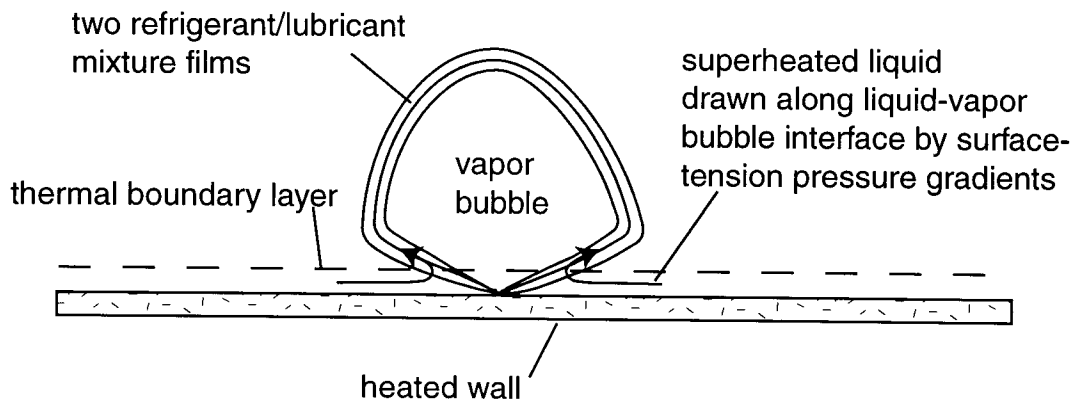
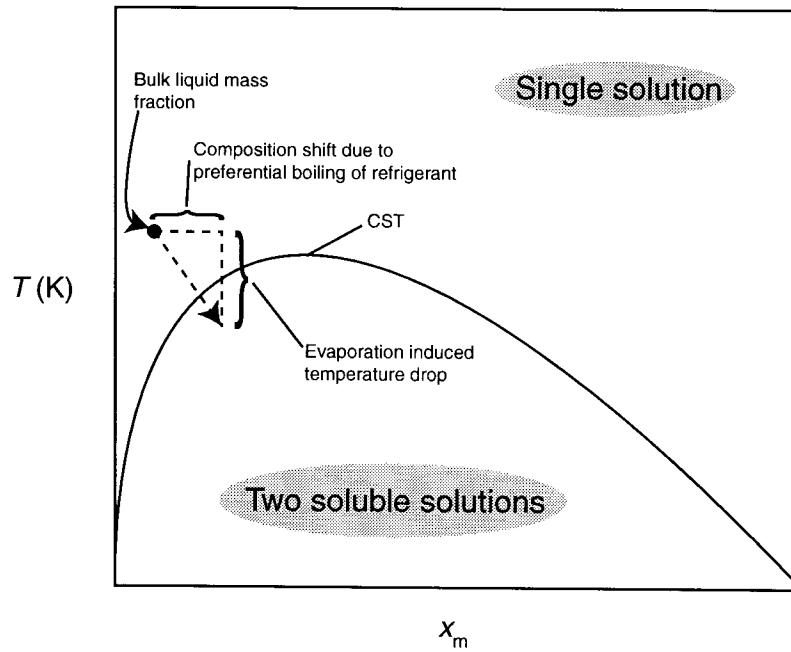


Fig. 27 Mechanistic explanation of the influence of lubricant miscibility on boiling