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An empirical correlation for electrohydrodynamic enhancement of natural convection

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Abstract

A correlation for predicting the extent of electrohydrodynamic enhancement of natural convection from heated horizontal cylinders is presented. This correlation is supported with results from two different experiments; the first involves natural convection from a thin platinum wire immersed in R-123 with a uniform electric field, while the second involves natural convection from a flooded tube immersed in R-123 in a non-uniform electric field. The Nusselt number enhancement is correlated in terms of a "corrected electrical Rayleigh number", Ra_{El}, to account for the effect of a non-uniform electric field on natural convection. The correlation is valid for the range $4.0 \times 10^3 \leq Ra_{El} \leq 8.0 \times 10^8$. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The ability of a high voltage electric field to enhance heat transfer in a dielectric or weakly conducting fluid has been known since Chubb [1] performed his experiments with water. Jones [2] and Allen and Karayiannis [3] conducted reviews of electrohydrodynamic (EHD) enhanced heat transfer. Among other topics, these exhaustive reviews covered in detail the effect of EHD on buoyant convection; both reviews indicate that the seminal work on EHD enhancement of natural convection from horizontal heated wires and cylinders is represented by the work of Kronig and Schwarz [4] for gases, and Ahsmann and Kronig [5] for liquids.

Existing correlations for EHD enhancement of natural convection from cylinders and wires apply only to uniform electric fields; they also cover a narrow range of the electrical number, which is related to the electric field strength. To this end, the objective of this study was to extend the range of applicability of existing correlations to higher electric Rayleigh numbers, and to develop the means of generalizing the correlations so that they can be applied for cases with non-uniform electric fields. Two experiments were performed to elucidate the nature of the electric forces and quantify the extent of heat transfer enhancement in natural convection with either a uniform or non-uniform electric field. The first set of experiments measured EHD enhancement of natural convection from a thin platinum wire submerged in R-123 with an applied uniform electric field. The second set of EHD-enhanced convection experiments was performed using a tube-in-tube heat exchanger with a non-uniform electric field.

Kronig and Schwarz [4] developed a non-dimensional electric Rayleigh number that correlated the extent of natural convection Nusselt number enhancement by an electric field. Their research was limited to

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Nomenclature

A, B	constants used in Eq. (13)
D	heater surface diameter (m)
E	electric field strength (V/m or N/C)
El	electrical number defined in Eq. (2)
$El_{Corrected}$	corrected electrical number defined in Eq. (7)
$\bar{F}_v$	electric force density on a liquid dielectric (N/m^3)
g	gravitational acceleration (m/s^2)
L_1	length scale used in Eq. (7) (m)
L_2	length scale used in Eq. (7) (m)
Nu	Nusselt number
ΔNu	increase in Nusselt number due to applied electric field
n	constant used in Eq. (10) given by Eq. (11)
Pr	Prandtl number
q	free charge density (C/m^3)
Ra	Rayleigh number
Ra_{El}	electric Rayleigh number
T	temperature (°C)
T_S	heater surface temperature (°C)
T_∞	pool temperature (°C)
u	velocity (m/s)

Greek symbols

α	thermal diffusivity (m^2/s)
β	volumetric thermal expansion coefficient (K^{-1})
ε	dielectric constant
ε_0	free space electric permittivity (F/m or C/V m)
μ	liquid dynamic viscosity (Pa s)
ν	kinematic viscosity (m^2/s)
ρ	liquid density (kg/m^3)

Subscripts

1, 2	similar conditions

gas flows and for electric Rayleigh numbers up to 100. Ahsmann and Kronig [5] used the same formulation to predict natural convection enhancement for liquids up to an electric Rayleigh number of 1000. Rutkowski [6] examined the effect of EHD on natural convection from a heated horizontal wire immersed in liquid nitrogen. As a result, he expanded the range of the correlation to electric Rayleigh numbers near 3.0×10^5. This study extends the range of the correlation to an electric Rayleigh number of 8.0×10^8, with either a uniform or non-uniform electric field.

The electric force density on a dielectric fluid under the influence of an electric field is given by [7]:

$$\bar{F}_v = q\bar{E} + \frac{1}{3}\varepsilon_0(\varepsilon - 1)E^2\frac{d\varepsilon}{dT}\nabla T + \frac{1}{6}\varepsilon_0(\varepsilon - 1)(\varepsilon + 2)\nabla E^2 \qquad (1)$$

Eq. (1) has been modified to remove the direct density dependence of the liquid dielectric by using the Clausius–Mossotti law [7]. The first term on the right is due to the Coulomb force upon a charged particle in a dielectric fluid. Such direct action of an electric field upon a charged particle is called electrophoresis. The second term is called electroconvection and represents the force density due to variation in the dielectric constant, ε, with temperature. In single phase heat transfer, this force density term is affected by the thickness of the thermal boundary layer. Finally, the last term is due to dielectrophoresis, which represents the translational motion of neutral matter caused by polarization effects in a non-uniform electric field.

The electric force acting on dielectric liquids augments heat transfer by applying an additional force on the fluid that aids the buoyancy force. At a fixed heat flux, an increase in the heat transfer coefficient necessarily results in a decrease in the temperature difference between the surface and the fluid. Since, the electroconvective force requires a gradient in the dielectric constant, which arises from the temperature gradient, heat transfer enhancement is affected by the temperature difference. On the other hand, the dielectrophoretic force only requires a gradient in the square of the electric field and is, therefore, essentially unaffected by the temperature gradients.

Kronig and Schwarz [4] developed a characteristic electrical number analogous to the Grashof number in buoyant convection. The non-dimensional electrical number was used to define an electric Rayleigh number, $Ra_{El} = El \times Pr$, which, in turn, was used to describe the enhancement of natural convection in gases. The electrical number is a ratio of the electric force to the viscous force. Ahsmann and Kronig [5] corrected this model for liquids by using a modified electrical number. Rutkowski [6] performed liquid nitrogen experiments under the influence of an electric field. His investigation extended the range of this liquid model and proposed a correlation to quantify the enhancement in Nusselt number as a function of the electric Rayleigh number.

The electrical number, as modified by Ahsmann and Kronig, is given by:

$$El = \frac{\rho \frac{d\varepsilon}{dT} D^2 \Delta T \varepsilon_0 E^2}{\mu^2} \tag{2}$$

This form of the electrical number assumes that the second term of Eq. (1) is the dominant term in the electric force equation. This assumption is true for cases involving a uniform electric field or a weakly divergent non-uniform electric field, where the second term is much larger than the third term in Eq. (1).

Kronig and Schwarz proposed the following equation to account for the increase in heat transfer as a result of an applied electric field above its original natural convection value. The increase in the Nusselt number is correlated in terms of the electric Rayleigh number:

$$\Delta Nu = f(El \times Pr) = f(Ra_{El}) \tag{3}$$

Rutkowski fitted Ahsmann and Kronig's data and his own liquid nitrogen data to a correlation of this form. Eq. (4) shows the correlation for organic fluids, while Eq. (5) shows the correlation for the liquid nitrogen data.

$$\Delta Nu = 0.00035 Ra_{El}^{1.1} \quad 1.5 \times 10^1 \le Ra_{El} \le 1.0 \times 10^3 \tag{4}$$

$$\Delta Nu = 0.68 Ra_{El}^{0.4} \quad 1.0 \times 10^4 \le Ra_{El} \le 3.0 \times 10^5 \tag{5}$$

In general, as the electric Rayleigh number increases the heat transfer coefficient increases. In other words, larger electric field strength results in a larger heat transfer enhancement.

The models described by Eqs. (4) and (5) assume that the buoyancy force as described by the Rayleigh number is uncoupled from the electric Rayleigh number. However, both effects are coupled, in as much as they are both dependent on the temperature distribution which, in turn, is affected by the velocity distribution. Nevertheless, the data are normally correlated in terms of a Nusselt number enhancement, since ΔNu is often significantly higher than the original value of Nu.

The third term of Eq. (1) becomes significant when the electric field is highly non-uniform; in such a case, the electrical number, defined in Eq. (2), must be modified since its current form accounts only for electroconvection. A complete derivation of the modified electrical number may be found in Ref. [8].

Kronig and Schwarz [4] used a dynamic similarity technique to develop the dimensionless groups needed to identify the relationship between the electric force and the viscous force. From the momentum equation and the electrical force equation, the following relationship was developed:

$$\frac{(F_v)_1}{(F_v)_2} = \frac{(\mu \nabla^2 u)_1}{(\mu \nabla^2 u)_2} \tag{6}$$

where F_v is the electric force density, μ is the dynamic viscosity, u is the velocity and the subscripts 1 and 2 represent two dynamically similar conditions. Ahsmann and Kronig [5] substituted the second term of Eq. (1) for F_v to determine their electrical number definition for liquids. To account for dielectrophoresis, Pascual [8] substituted the sum of the second and third terms of Eq. (1) into Eq. (6) for F_v to determine the corrected electrical number. Since the momentum and energy equations are coupled, both are needed to determine the correct scaling of the linear dimensions and the velocity. In terms of the original electrical number, the corrected electrical number is [8]:

$$El_{Corrected} = \left[1 + \frac{1}{2} \frac{\varepsilon + 2}{\frac{d\varepsilon}{dT} \Delta T} \frac{L_1}{L_2} \right] El \tag{7}$$

In deriving the above equation, the length and velocity scales were:

$$\text{Length scale} \propto L_1 (Ra_{El})^{-1/2} \tag{8}$$

$$\text{Velocity scale} \propto \frac{\alpha}{L_1} (Ra_{El})^{1/2} \tag{9}$$

where, α is the thermal diffusivity, L_1 represents the same length scale as that in the original electrical number, namely the diameter D, and L_2 represents the length scale associated with the divergence of the electric field. Here, L_2 is selected as the shortest distance between the highest and lowest equipotential lines in the system. The electric field strength used in calculating the corrected electrical number above represents the average value over the heat transfer surface. Such an average can be estimated from the distribution of electric field strength near the surface, which can be calculated by numerically solving Laplace's equation [8].

2. Experimental apparatus

Two different experimental investigations were performed. The first investigation involved heat transfer from a horizontal platinum wire under the influence of a uniform electric field submerged in a pool of R-123.

A schematic diagram of the experimental apparatus is included as Fig. 1.

A platinum wire, 0.13 mm in diameter and 5.6 cm long, was used as the heat source. Fig. 2 shows the platinum wire attached to its power supply, as well as its current and voltage measuring devices. Since the resistance of the platinum changes linearly with temperature, this wire provided a method to record the heater surface temperature, as well as the heat flux. Prior to commencing the experiments, the wire was calibrated

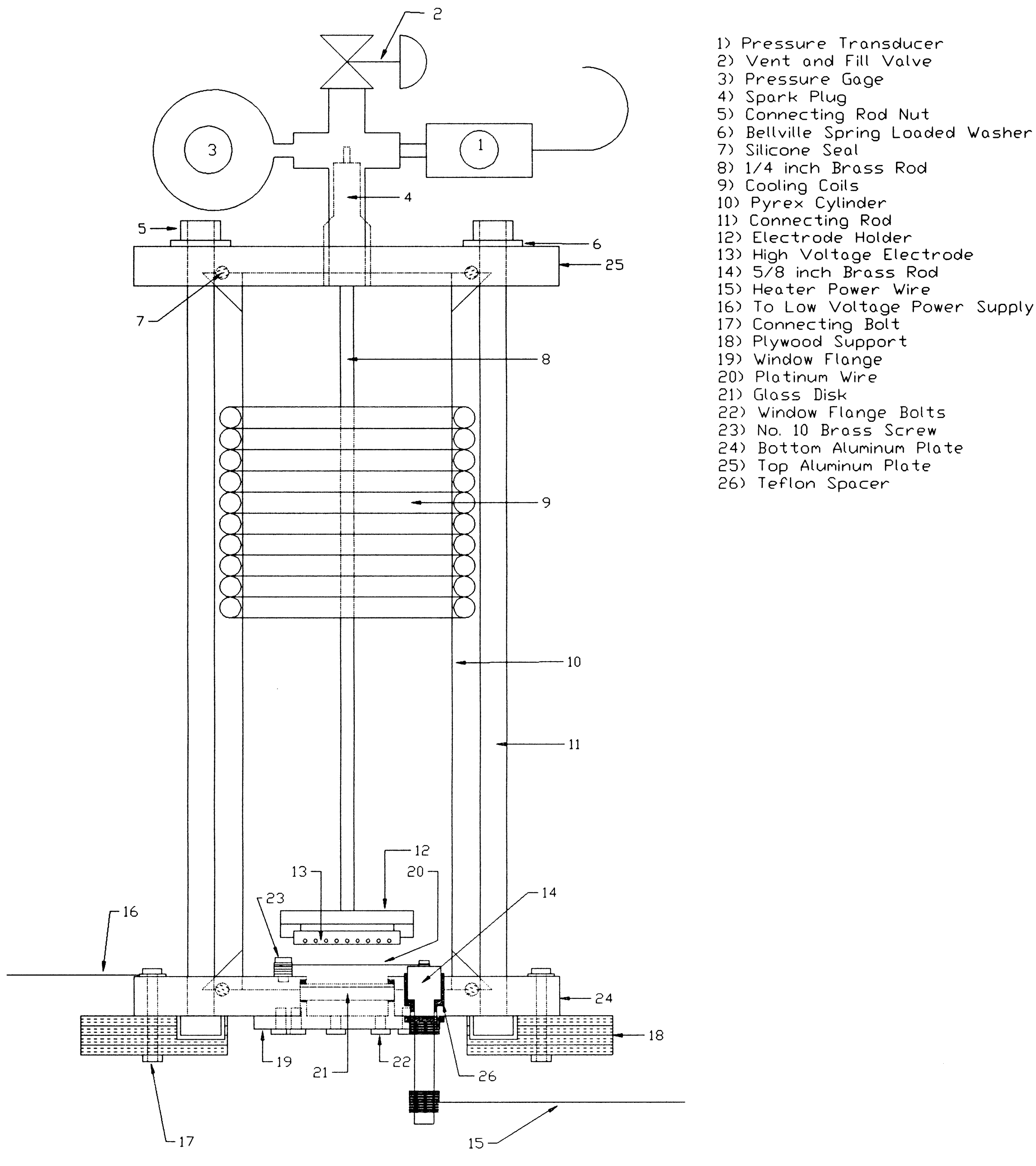

Fig. 1. Platinum wire experimental test facility.

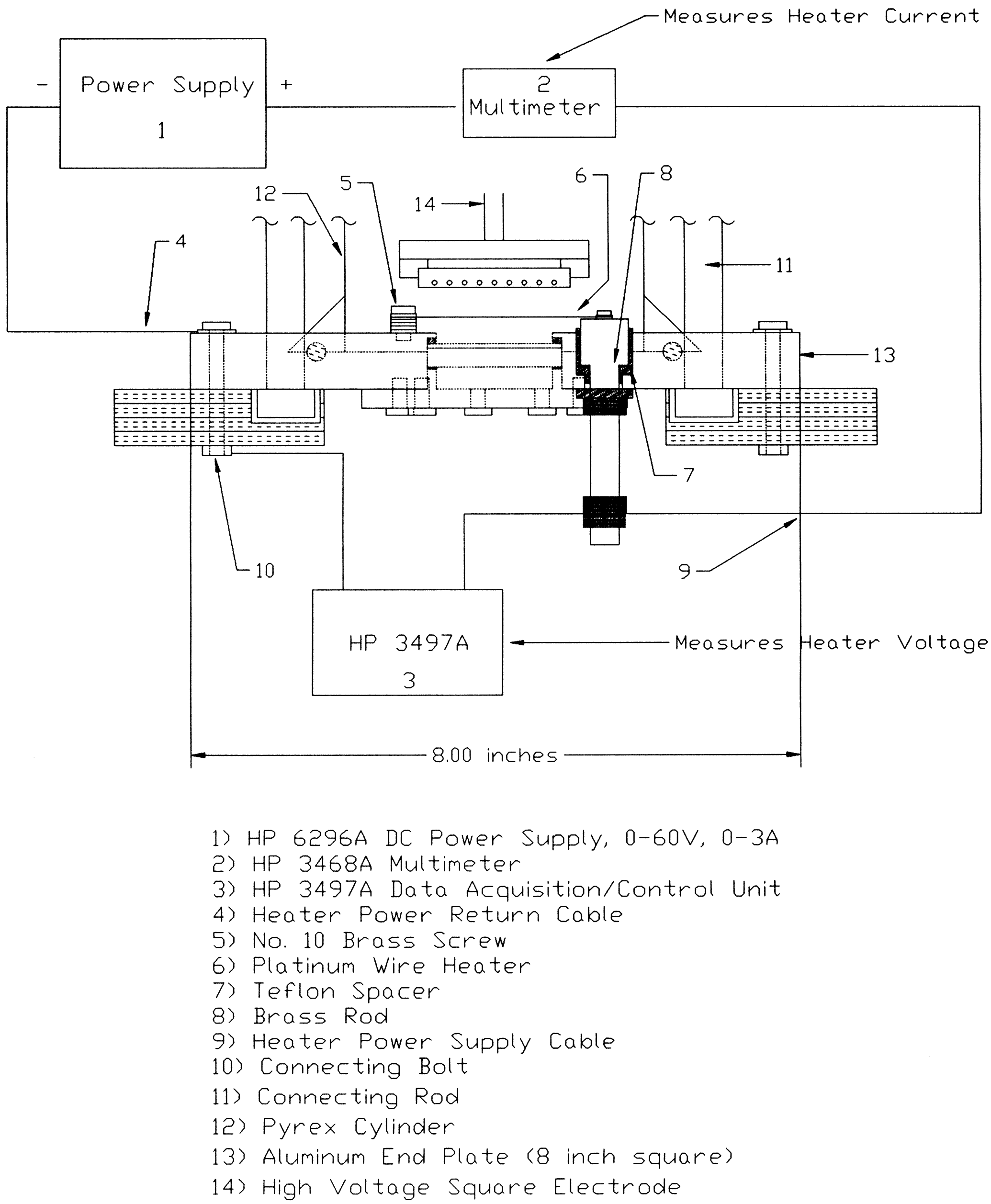

Fig. 2. Platinum wire heater power supply system.

against a standard thermometer. From the calibration results, a 0.001 Ω change in platinum wire resistance was equivalent to a 0.6°C change in surface temperature. A multimeter (HP3468A) was used to measure the current supplied to the wire, while an external bus data acquisition system (HP3497A Data Acquisition/Control Unit) was used to measure the voltage supplied to the wire. Based on the manufacturer's calibration, the multimeter was accurate to 0.14% of the reading for currents <1 A and 1% of the reading for currents >1 A. Also, based on the manufacturer's calibration, the data acquisition system was accurate to 0.002% of the reading.

The housing of the experimental apparatus was made from a single 100 mm diameter, 30 cm long, Pyrex cylinder with grooves in both ends to accept oring seals. Aluminum plates were attached to both ends of the Pyrex cylinder to seal the cylinder from the atmosphere. The end plates also provided penetrations for the connections to the interior of the system.

Three penetrations were made in the bottom aluminum plate. The first penetration was used to supply power to the platinum wire. The second penetration allowed for the placement of a calibrated thermocouple in the R-123 pool. The third penetration provided a viewing window used for imaging bubble dynamics under boiling conditions. As seen in Figs. 1 and 2, the platinum wire was attached to the top of a 5/8 in. diameter brass rod, which was electrically isolated from the bottom aluminum plate using a Teflon spacer. The other end of the platinum wire was attached by a brass screw and brass washers to the bottom aluminum plate. In this manner, the bottom aluminum plate was used to complete the electrical circuit for the heater.

The top aluminum plate was also used to seal the Pyrex cylinder from the atmosphere. Two penetrations

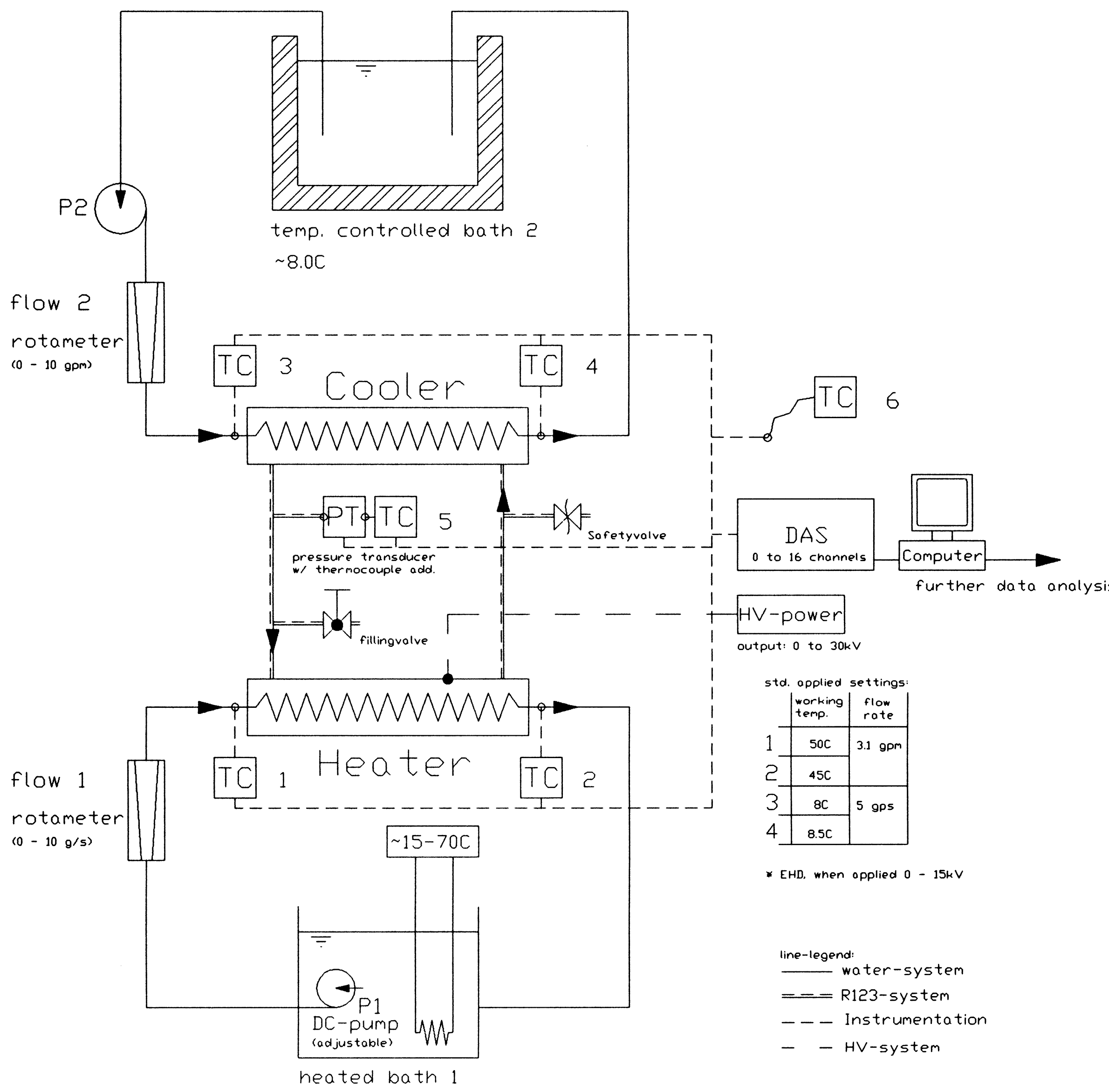

Fig. 3. Tube-in-tube heat exchanger experimental test facility.

were made in the top end plate. The first penetration allowed for attachment of a pressure transducer, pressure gage, and a shut off valve. The valve was used for evacuating and filling the system. The calibrated pressure transducer was used to verify the saturation conditions of R-123 inside the cylinder. The second penetration located in the center of the top plate was used for an automotive spark plug. The spark plug provided a reliable and inexpensive high voltage feedthrough. A brass rod, 1/4 in. diameter, was attached to the bottom of the spark plug. As seen in Fig. 2, a square wire mesh was attached to the bottom of this brass rod. This square mesh located 10 mm above the platinum wire was used to create the uniform electric field on the heater surface. A 0–30 kV high voltage power supply (Glassman Model PS/MJ30P0400-11) was used to supply voltage to the square mesh through the spark plug and brass rod. The platinum wire and the high voltage electrode were both submerged in the pool of liquid R-123, which was at saturation conditions. A more detailed description of the apparatus and experimental procedure can be found in Pascual [8].

The second experimental apparatus involved EHD enhancement for natural convection in a tube-in-tube heat exchanger under the influence of a non-uniform electric field. The experimental apparatus, Fig. 3, consisted of two tube-in-tube heat exchangers, approximately 640 mm in length. The first is labeled "heater", while the second is labeled "cooler". The shell side of both the heater and the cooler were charged with R-123. The 6.35 mm outside diameter brass inner tube of the heater was surrounded by high voltage electrodes, Fig. 4, so that the tube and electrodes were completely submerged in liquid R-123. Heated water was supplied to the tube side of the heater, while chilled water was supplied to the tube side of the cooler. The cooler was used to remove the heat added in the heater so that steady state conditions could be maintained. It was placed above the heater to promote natural circulation through the connecting loop piping. Experiments were conducted for both natural convection and boiling conditions in the heater. The experiments presented here deal only with natural convection conditions.

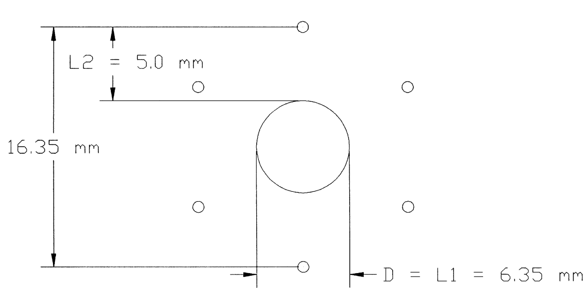

Fig. 4. Electrode arrangement for tube-in-tube heat exchanger experiment.

Around the perimeter of the inner tube, high voltage electrode wires were placed 60° apart and 5.0 mm away from the inner tube in order to generate the non-uniform electric field (Fig. 4). A seamless nichrome wire was mounted over two specially designed nylon electrode holders. The electrode array was kept in position by these spring-loaded electrode holders. A 0–30 kV high voltage power supply was connected to the seamless wire through a spring loaded voltage feedthrough. The spring in the feedthrough ensured electrical contact with the seamless nichrome wire.

The inlet and outlet temperature of the heated water in the heater were measured with calibrated thermocouples in order to determine the heat transfer rate from the heated water to the R-123. The water volumetric flow rate was measured using a calibrated rotameter. On the shell side of the heater, the R-123 pool temperature along with the saturation pressure were measured to verify saturation conditions. A more detailed description of this apparatus and the experimental procedure is available in Ref. [9].

3. Results

In both the platinum wire experiments and the heat exchanger experiments, the orientation of the electric field was not important to the results. For both experiments, the heat transfer surface was grounded and the high voltage electrodes were at a positive voltage. The polarity was not reversed for either of these experiments; however, based on Eq. (1), neither electroconvection nor dielectrophoresis would have been affected by the polarity of the electric field because both these forces are proportional to the square of the electric field or its gradient.

For the platinum wire experiments, the voltage and current to the wire were measured and used to calculate the power input, and hence, the heat flux. For single phase convection experiments, heat fluxes up to 5 W/cm^2 were examined. Based on uncertainty analysis, the heat flux was accurate to 2.2% of its calculated value. The resistance of the wire was calibrated and used to measure the surface temperature. The surface temperature was known to an accuracy of 3.0°C for heat flux levels greater than 4 W/cm^2 and to an accuracy of 0.4°C for heat flux values less than 4 W/cm^2. The calibrated thermocouple used to measure the pool temperature was accurate to $\pm$0.005°C. Single phase experiments were performed with no applied electric field first to establish a baseline for comparison. Most other single phase experiments with an applied electric field were performed at 10 kV; however, some 15 kV experiments were also performed. The uncertainty in the high voltage reading was 1% of the reading. For the uniform electric field platinum wire experiments, the electrical number was calculated using Eq. (2). The fluid properties of liquid R-123 were obtained from the ASHRAE Handbook [10], while the dielectric constant and its dependence on temperature were found in Ref. [11]. The diameter of the wire, D, was used as the characteristic length. The temperature difference, ΔT, between the surface of the wire and the R-123 pool temperature was used in both the Rayleigh number and the electric Rayleigh number. The electric field strength at the heat transfer surface, E, was calculated from a numerical solution to Laplace's equation, as described by Pascual [8]. Typical parameter values for the platinum wire experiments under the influence of a uniform electric field at a heat flux of 2.62 W/cm^2 and an electrode voltage of 10 kV are presented in Table 1. Based on uncertainty analysis, the uncertainty in the electrical number and the electric Rayleigh number was estimated to be 12.8% for heat flux values less than 4 W/cm^2 and 20.2% for heat flux values greater than 4 W/cm^2.

The heat transfer enhancement, ΔNu, due to the electric field was calculated from the experimental data. The natural convection heat transfer coefficient without an electric field was calculated using the standard correlation for heat transfer from a long horizontal cylinder developed by McAdams [12]. This correlation was modified by Paul and Abdel-Khalik [13] for Rayleigh numbers less than 10^4 and is given by:

$$Nu = (1.000)Ra^n \tag{10}$$

where

$$n = 0.130 + 0.0125 \log(Ra) \tag{11}$$

and

$$Ra = \frac{g\beta(T_S - T_\infty)D^3}{\nu\alpha} \tag{12}$$

This value of the Nusselt number was then subtracted from the experimental Nusselt number determined from the heat flux and temperature difference data, to obtain the experimental value of the Nusselt number enhancement, ΔNu. The uncertainty in the ΔNu value was estimated to be 9% for heat flux values less than 4 W/cm^2 and 26% for heat flux values greater than 4 W/cm^2. All the experimental data are available in Ref. [8].

Fig. 5 shows the results of the experimental ΔNu versus the electric Rayleigh number. The data for the organic fluids were from the experiments performed by Ahsmann and Kronig [5]. The liquid nitrogen data were from the experiments performed by Rutkowski [6]. As can be seen in Fig. 5, the platinum wire R-123 experiments overlap the electrical Rayleigh number range for the liquid nitrogen data.

For the flooded heat exchanger investigation, the pool temperature was maintained at a constant value of approximately 20°C by removing heat through the cooler. Experiments were first performed without an applied electric field to establish a baseline for comparison. Experiments were then conducted at different electrode voltages ranging from 1 to 15 kV. Experiments were conducted with different hot water inlet temperatures, 30–60°C, resulting in total heat transfer rates between 40 and 160 W. For this article, only the

Table 1
Comparison of parameters for two sample experiments

Parameter	Uniform electric field	Non-uniform electric field
Liquid density (kg/m^3)	1470	1465
$d\varepsilon/dT$ (C^{-1})	0.0195	10.01951
Dielectric constant	N/A	4.57
Diameter (m)	0.00013	0.00635
Electric field length scale (m)	N/A	0.005
Temperature difference (°C)	12.1	7.93
ε_0 (F/m)	8.85E−12	8.85E−12
Electric field (V/m)	1.62E+06	3.33E+05
Dynamic viscosity (Pa s)	0.000432	0.000425
Heat capacity (J/kg K)	981	987
Thermal conductivity (W/m K)	0.077	0.077
Prandtl number	5.50	5.45
Electrical number	730	49753
Corrected electrical number	N/A	1.39E+06
Electric Rayleigh number	4017	7.59E+06

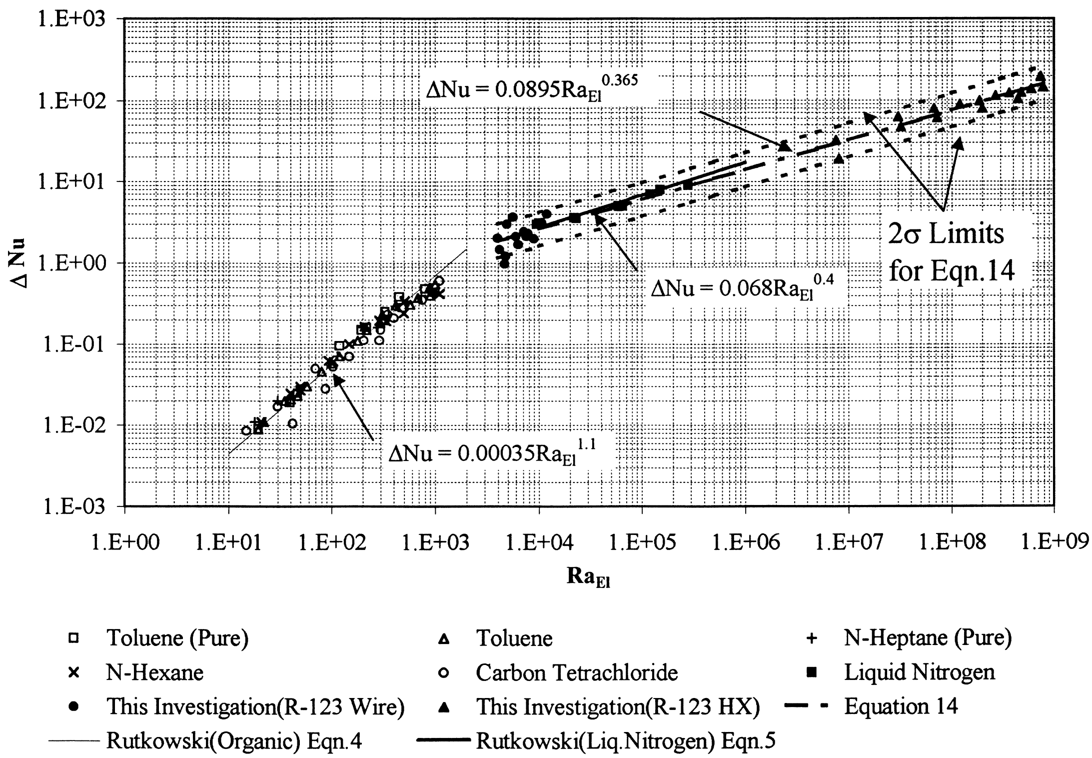

Fig. 5. Experimental data and correlation.

30 and 40°C inlet water temperature experiments with an applied electrode voltage up to 10 kV were considered since only single phase natural convection data were analyzed. Many additional experiments involving nucleate boiling were also performed using higher hot water temperatures (see Ref. [9]). The corrected electrical number, Eq. (7), was used to calculate the electric Rayleigh number because the electric field in this case was highly non-uniform. The average electric field strength, E, at the outer surface of the inner tube, required in the definition of the corrected electrical number, was calculated from a numerical solution to Laplace's equation, as described in Ref. [8]. Even though the electric field was highly non-uniform, the electric field strength at the heat transfer surface was nearly constant, which simplified the average electric field strength calculations for use in Eq. (7). The overall heat transfer coefficient was first determined from a heat exchanger analysis of the tube-in-tube heat exchanger. The three components of the overall heat transfer coefficient were determined by using: (1) forced convection correlations for flow inside the inner tube, (2) radial conduction through the brass tube wall, and (3) natural convection from a long heated horizontal cylinder for the shell side heat transfer. The experimental value of ΔNu was determined by subtracting the calculated overall heat transfer coefficient from the total experimental Nu. The uncertainty in the ΔNu was estimated to be 10%. A typical calculation for the corrected electrical number at a voltage of 1.0 kV and a surface temperature of 30°C is presented in Table 1. For L_1, the outside diameter of the brass inner tube, 6.35 mm, was used. For L_2, the distance between the tube surface and the electrode assembly, i.e. the shortest distance between the highest and lowest equipotential lines, 5.0 mm, was used. The uncertainty in the corrected electrical number and the electric Rayleigh number was estimated to be 3%. All the experimental data are available in Ref. [9].

The single phase heat exchanger experiments are also plotted on Fig. 5. As can be seen in the figure, these experiments extend the range of the data to electric Rayleigh numbers as high as 8×10^8. With this final data set, a new correlation can be determined that incorporates the data obtained by Rutkowski using liquid nitrogen [6], along with the data from the two newly investigated R-123 experiments presented here.

A regression analysis was performed on the experimental data presented in Fig. 5 with the exception of the organic liquids. The data were fitted to a correlation of the following form:

$$\Delta Nu = ARa_{El}^{B} \tag{13}$$

where the coefficients were determined to be:

$$\Delta Nu = 0.0895Ra_{El}^{0.365} \tag{14}$$

Eq. (14) is also plotted in Fig. 5. In addition, the plotted dashed lines represent twice the standard error of ΔNu above and below the model. The coefficient of determination, R^2, was calculated to be 0.9815 while the alpha risk on the exponent was calculated to be effectively zero. Therefore, the above correlation represents the data well, and the exponent is statistically significant. This particular form of the correlation is the same form as the one presented by Rutkowski [6], Eq. (5). Eq. (14) was developed based on experiments from various liquids at different temperatures, different designs, different electric field strengths, and different electric field geometries. Therefore, this correlation is applicable over a range of electric Rayleigh numbers from 4×10^3 to 8×10^8 for various experimental conditions.

For both sets of experiments presented, the value of Nusselt number enhancement, ΔNu, was often higher than the original Nu value itself. For the heated wire experiments, Nu varied between 1.61 and 1.84, while ΔNu varied between 1.0 and 5.4. For the heat exchanger experiments, Nu varied between 21 and 27, while ΔNu varied between 20 and 194. For an electrical potential as low as 1 kV in the heat exchanger experiments, the buoyancy was already smaller than the electric field effects (i.e. ΔNu is larger than the original Nu value). In addition, dielectrophoresis accounted for the large enhancement in heat transfer in the heat exchanger experiments, when compared to the enhancement encountered in the heated wire uniform electric field experiments.

4. Conclusion

Eq. (14) represents a new correlation that quantifies the enhancement to natural convection from a horizontal cylinder as a result of an applied electric field. This new correlation was based on data obtained in two different experiments, along with previous data presented by Rutkowski. These two new experimental investigations both confirm and extend the range of the previous investigations. Using the same form of the electrical number, the platinum wire experiments overlapped the liquid nitrogen data obtained by Rutkowski. Using the corrected electrical number, Eq. (7), to account for the strong divergent electric field on the heat exchanger experiments, the model was extended to modified electric Rayleigh numbers up to 8×10^8. The new correlation represents the main result of this investigation; it allows for prediction of natural convection enhancement over a large range of electric field strengths, with either a uniform or non-uniform electric field.

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