EHD COOLING SYSTEM TECHNOLOGY TOWARDS COMMERCIAL ACCEPTANCE

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Abstract— The main aim of Electrohydrodynamic (EHD) is to reduce the heat exchanger size by using heat transfer enhancement. The EHD is mostly used for aircraft industry for heat transfer enhancement. Engineers can change their design approach and plan for minimal loads, resulting in heat exchangers more suitable to avionic geometries, allowing for additional payload space. During normal and operationally-induced increased heat loads, an EHD cooling system could automatically adjust the heat exchanger's capacity to handle these loads. The research goal is to prove aviable EHD heat exchanger concept while moving the technology towards commercial acceptance. Two concepts are investigated. One considers a common metallic material, while the other investigates ceramic construction. Both concepts show promise and advance the technology. The metallic EHD-enhanced heat exchanger yielded heat transfer rates nearly three fold compared to conventional heat exchangers, thus introducing a potential for three times reduction in the heat exchanger size.

Keywords— Electrohydrodynamic (EHD) heat transfer enhancement; Metallic Compact Heat Exchanger; Ceramic Compact Heat Exchanger..

I. INTRODUCTION

Compact heat exchangers have been studied in great detail, and their heat transfer characteristics have been proven over many years. More recently, electrohydrodynamic (EHD) heat transfer enhancement, an active enhancement method, has produced dramatic improvements in the heat transfer coefficients of many heat exchanger fluids. Experiments have shown promising results, but development of practical heat exchangers is still needed. This study introduces the EHD enhancement technique into a metallic, five-port, compact heat exchanger and proves the feasibility of miniaturization in a simple tube-in-tube heat exchanger. Additionally, the introduction of ceramics in the construction of the heat exchanger shows potential advantages previously considered unattainable for practical applications.The EHD technology, due to its potential in increasing heat loads and minimizing size requirements, has enormous potential application in the aircraft industry, where the age-old doctrine of "higher, faster, farther" has been the guiding principle of each design iteration over the decades. This doctrine is not without its limits, howev er, and it would be appropriate to add "affordable and smart" to the list of principles. The main challenge for the aircraft industry in the 21st century is to provide technologically superior products and services at an affordable price. Implementation of EHD into aircraft design can help meet this challenge and design approach. The development of such technologically superior heat exchangers at a reduced size and weight would be a phenomenal achievement. Engineers could design heat exchangers for minimal or average heating or cooling loads such that any needed increase in heat transfer could be handled by a simple, controllable applied electric field or EHD potential (voltage) adjustment. How much "smarter" could a design be? Typically, the voltages required to enhance the heat transfer associated with EHD are accompanied by very low current values, resulting in power consumptions that are very small, and are much smaller than traditional technologies on the same enhancement basis. The most significant drawback when discussing most enhancement techniques, pressure drop, can also be significantly reduced using EHD when compared to other techniques, both active and passive. This controllable feature of EHD heat exchangers can provide highly stable temperatures so that the reliability of any electronic equipment, cooled by the fluid passing through the heat exchanger, is improved.

II. EHD ENHANCED HEAT TRANSFER FUNDAMENTALS

2.1 Introduction

This chapter provides an introduction to various categories of heat exchanges first, and will be followed by a review of the fundamental aspects of the electrohydrodynamic enhancement of heat and mass transfer. In the last section of this chapter, a review of previous related work is presented. 2.2 Size Classification Compact heat exchangers are classified as such based on the area density, β, of the heat transfer surface. Area density is defined as the ratio between the heat transfer surface area and the corresponding flow volume of the fluid. The typical area density cutoff for a heat exchanger to be considered compact is approximately 700 m2/m3 (213 ft2/ft3) (London, 1980). This cutoff value translates to a tube with an equivalent circular, or hydraulic, diameter of 5.7 mm (.224 in.). Therefore, a heat exchanger employingchannels with a hydraulic diameter of 5.7 mm (0.224 in.) or less would be considered compact. For comparative purposes, the human lung has a β of almost 20,000 m2/m3 (6086 ft2 / ft3), with an equivalent hydraulic diameter of 0.1 mm or 100 microns (0.004 in.). Higher β geometries result in heat exchanger channels with smaller equivalent hydraulic diameters. A heat exchanger with area density in the range of 2500 m2/m3 (761 ft2/ft3) up to 10,000 m2/m3 (3,043 ft2/ft3) is considered sub-compact. A heat exchanger with area density greater than that of the sub-compact range is considered a micro channel heat exchanger, or over 10,000 m2/m3 (3,043 ft2/ft3). The present research deals with a sub-compact heat exchanger, with a β greater than 2500 m2/m3 (761 ft2/ft3) and less than 10,000 m2/m3 (3,043 ft2/ft3).

2.2 High Performance Characteristics

The EHD enhancement technique of heat transfer is an active form of heat transfer augmentation that utilizes the effect of electrically induced secondary motions that are produced when a high voltage, low current electric field is applied to a dielectric fluid medium. These secondary motions improve mixing in the bulk flow and increase the activity near the heat transfer surface, leading to heat transfer coefficients that are often an order of magnitude higher than those achieved by conventional enhancement techniques.

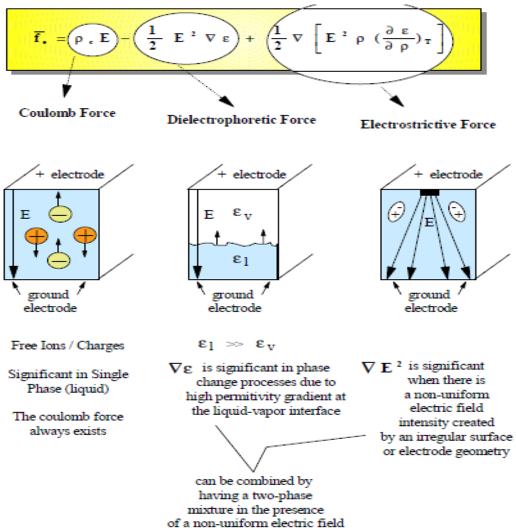

Figure 2.1 : EHD Body Force Equation

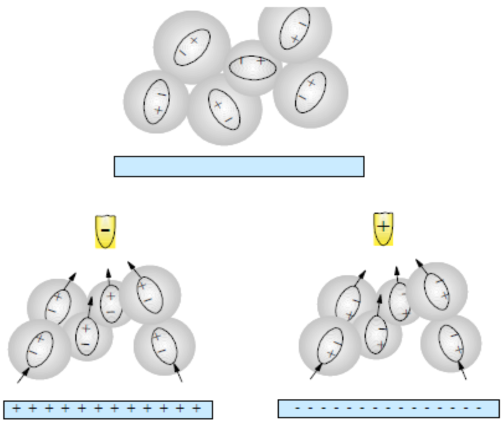

Figure 2.2 : EHD Polarization of a Dielectric Fluid

The magnitude and nature of the enhancement is a direct function of electric field and flow field parameters, as well as heat transfer surface conditions.

III. ALTERNATIVE HEAT EXCHANGER MATERIALS

3.1 Introduction

Most heat exchangers in use today are constructed of metallic materials. Ceramics are not used as frequently due to their inherent insulating properties. However, metals have their own drawbacks when used for an EHD heat exchanger. Metals serve as excellent conductors of both heat and electricity, but the metallic heat exchangers will not benefit from the electrical conduction necessary for EHD unless the heat exchanger is sufficiently insulated to allow a voltage to build up across the fluid medium. This insulation process is significantly easier to implement when compared to insertion of the EHD technology into a ceramic heat exchanger. There are only a handful of ceramic materials that actually have decent heat transport properties, and even fewer that display other desired properties needed for the EHD technique to be successful. Although there are few, those ceramic materials that have the potential for use in EHD heat exchangers are worth investigating due to the potential that the material possesses.

3.2 Ceramic Heat Exchangers

The high cost of energy has led industry to find methods of extracting usable heat from high temperature waste streams. The use of ceramics in the design of heat exchangers is relatively new, developing in the last 20 to 25 years. Certain unique ceramic properties allow formerly impossible applications to be achieved. Ceramics can be used in and designed for heat exchange applications because of their ability to retain many of their properties at elevated temperatures of above 800 °C. Such applications might include the recovery of heat energy from industrial waste heat processes. Another ideal property of ceramics is their hardness. This property lends itself to use in heat exchange processes where corrosive liquid and/or gases are used. Ceramic materials are ideal for use in heat exchangers in specific processes and applications (Heinrich, 1990). Chemical applications include the elevation of acid concentrations and heat recovery of concentrated hot acids. Industrial applications include preheat treatment of combustion air by the flue gases of industrial furnaces. Thermal cleaning systems' corrosive flue gases can be preheated and the exhaust gases can be cooled down below the dew point of the cleaning acid.

3.3 Material Background

There are three main categories involved with the science of materials: metals, non-metals (or gases) and nonmetallic elemental solids (NMESs). Very few solids are used in their natural, pure form; rather solids are engineered for performance based on their intended use. Engineered solids include engineered metals, polymers, and ceramics, or semi-conductors. The mechanical properties of solids depend largely on the type of bonding which holds the molecules together. Metals use metallic, or ionic, bonding, where valence electrons are given up to fill another molecule's electron shell. Polymers use covalent bonding, wherein the valence electrons are shared between molecules, which bond the molecules together and provides a type of secondary bonding that holds the carbon chains together.

3.4 Ceramic Properties of Interest to Heat Exchanger Design

As with all engineered materials, ceramics have both detrimental and beneficial properties, which can be manipulated through the use of composites to degrade unwanted properties, or enhance desired properties. In pure ceramic compounds, certain properties are unique to ceramics simply because of their structure. The properties discussed below have been selected due to their direct or indirect relation to the thermal interests of heat exchanger design.

Atomic Packing Factor: Many properties exhibited by ceramic compounds are determined by their crystal structure. The arrangement of the unit cell and the location of the compound's cations and anions (positive and negative ions) dictate the crystal structure. According to Colling (1995), a useful parameter for understanding ceramics is the atomic packing factor (APF). This parameter is the volume fraction of atomsoccupying the unit cell and can be determined from the atomic radius, the geometry of the unit cell, or the density of the material; the general expression is:

$$APF = \frac{(No.\,of\ atoms\ per\ unit\ cell)(vol.\,of\ each\ atom)}{Vol.\,of\ unit\ cell} \qquad 3.1$$

IV. EXPERIMENTAL APPARATUS AND PROCEDURE

4.1 Introduction

This chapter describes the experimental apparatus and procedure involved in the present study. The setup is a dual loop designed for the heat exchanger incorporating a counter-flow pattern. The heat exchanger designs are also discussed in addition to the loops to which they are connected. The setup is split up into two loops and will be described in order as: a. Primary Loop, and

Details of each portion of the dual loop and each test section are discussed fully in the following sections.

4.2 Experimental Setup

The schematic of the entire apparatus, both the primary and secondary loops, is shown in figure 4.1. The primary loop travels through either the shell of the 5-port metallic heat exchanger and fluid flow field, or the upper portion of the ceramic heat exchanger. The secondary loop travels through either the tube bundle of the 5-port metallic heat exchanger, or the lower portion of the ceramic heat exchanger and the corresponding flow field.

4.3 Five-Port Metallic Heat Exchanger

The 5-port metallic heat exchanger is an actual, real-size, working heat exchanger in a complete unit. The HX is of a shell and tube bundle configuration shown in figures 4.3 and 4.4. The shell is of stainless steel tube with inside diameter of 0.652 in. (0.0166 m) and length of 6.3 in. (0.16 m). The tube bundle is constructed using 19 stainless steel tubes, each with an outside diameter of 0.0625 in. (0.0016 m) and inside diameter of 0.0545 in. (0.0014 m) The bundle is held in place in the configuration shown in figure 4.4 by two Teflon bundle caps. The tubes marked on the figure are connected together by thin wire threaded through machined channels in one of the bundle caps. These are then connected to the voltage source through the contact connection of the top tube, in the arrangement shown in Fig. 4.4. This contact connection is considered the 5th port.

4.4 Ceramic Heat Exchanger Test Section

The test section incorporates the ceramic heat exchanger and the frame in which it is housed. The test section frame's primary purpose is to seal the heat exchanger to prevent cross-contamination between the two fluids that are transferring heat. This setup uses a counter-flow configuration; the two fluids are flowing parallel to each other, but180° apart in flow direction. The frame also holds the charged electrodes to which high voltage for each flow field is supplied. Figures 4.5 through 4.9 show the test section in more detail.

Table 4.1 Thermo-Mechanical Properties

Material	Density (g/cm^3)	Expansion ($10^{-6}/K$)	Conductivity (W/m-K)	Hardness (kg/mm^2)	Resistivity (ohm - m)	Modulus (GPa)
SiC	3.10	4.50	200	2600	10^5	500
AlN	3.25	5.00	180	1100	10^{14}	331
B_4C	2.45	5.60	90	3200	10^8	450
BeO	2.86	8.50	280	1200	10^{14}	400
c-BN	3.49	4.80	200-900	2000	10^8	450

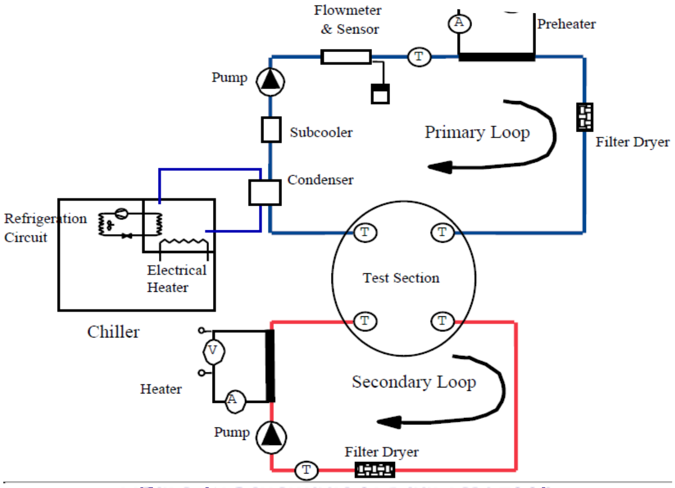

Figure 4.2 Five-port Metallic Heat Exchanger – pictured with a typical shell and tube heat exchanger of comparable capacity

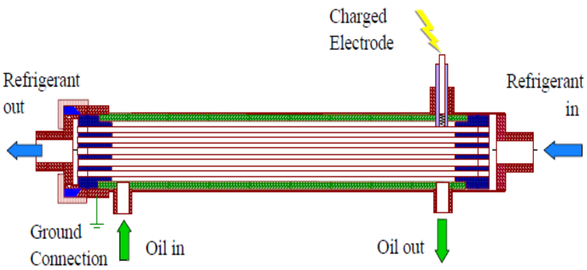

Figure 4.3 Five-port Metallic Heat Exchanger

V. RESULTS
5.1 Introduction

This chapter presents results and discussions of the experimental data for the heat exchanger enhancement studies on the five-port metallic and ceramic heat exchangers. The presentation is given in two parts. Part I will discuss results of the five-port metallic, EHD-enhanced shell-and-tube heat exchanger and part II of the chapter will discuss the results obtained with the ceramic heat exchanger. In each part, results for a base case (absence of EHD field) are discussed first and are followed by an EHD-enhanced case, where the effect of an applied EHD field on performance improvement of the base case is discussed.

5.2 Five Port Shell & Tube Bundle HX

The five-port, shell and tube bundle HX produced rather encouraging enhancement results on the overall heat transfer coefficient. R-134a was the fluid moving through the tube side of the shell and tube bundle. Tubes were smooth inside and had no provisions for enhancement. Two different fluids were tested in the shell side: PAO and JP8. For tests using both PAO and JP8, increasing the voltage affected the Reynolds number on the shell side by reducing the average temperature of the secondary loop. As discussed in chapter 4 and shown in Appendix A, the kinematic viscosity of PAO is very temperature dependent. The enhanced heat transfer, while producing more effective cooling of the PAO, produces a higher kinematic viscosity of the PAO strictly due to the reduced temperatures. Considering that kinematic viscosity is a variable in the equation for Reynolds number, the corresponding Re value, after voltage is applied, decreases. As discussed earlier in chapter 4, this resulting change in dimensionless operating parameters is not adjusted to maintain base conditions; rather the mass flux remains constant. One of the major selling points and expected applications of this technique is its on-demand feature. In other words, EHD can simply remove additional heat loads, above a certain design threshold, by increasing the applied voltage. No other adjustments to the cooling system are required to handle the increased load.

5.3 Ceramic Heat Exchanger

The research involved with the ceramic HX was challenging, exhaustive, and required painstaking care in assembling the heat exchanger and testing of it. Setbacks inherent with fabrication of this micro channel ceramic heat exchanger caused the project to surpass the time and money budget allocated towards the project, and disallowed concrete enhancement data from the effect of electric fields. Howeversuccessful base case data sets were collected and some of the difficulties encountered with the application of the electric field were solved, paving the way for future work. Prior to final failure, baseline data were taken using R-134a through the primary loop and PAO through the secondary loop. These tests all used a master base case of equal Reynolds numbers with a value of 500 for each fluid, an average oil temperature of 30°C (86°F), a saturated liquid refrigerant temperature of 20°C (68°F), an average refrigerant quality of 30 %, between inlet and outlet, and a heat flux of 5 kW/m² (1585 Btu/hr-ft²) based on an area that encompasses both sides of the ceramic plate.

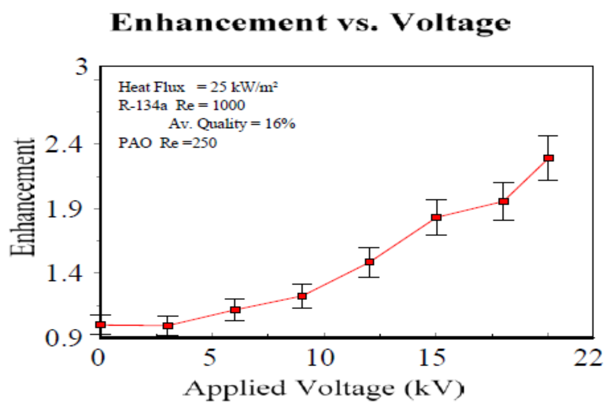

Figure 5.1 5-Port Metallic HX Enhancement Trand – Master Base Case

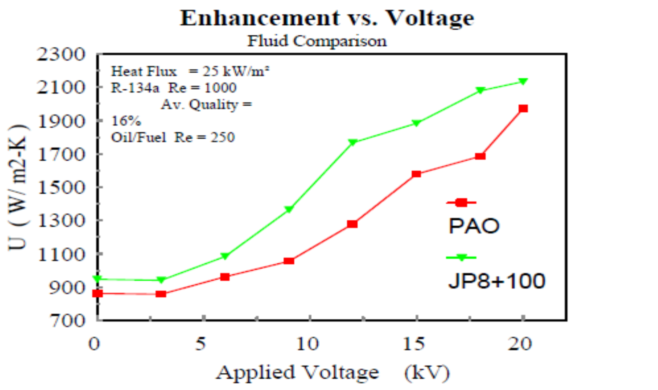

Figure 5.4 5-port Metallic HX Enhancement Comparison – Master Base Case

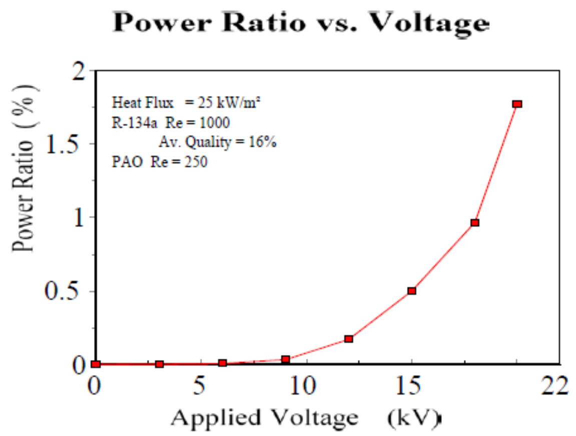

Figure 5.2 5-Port Metallic HX Power Ratio Trend – Master Base Case

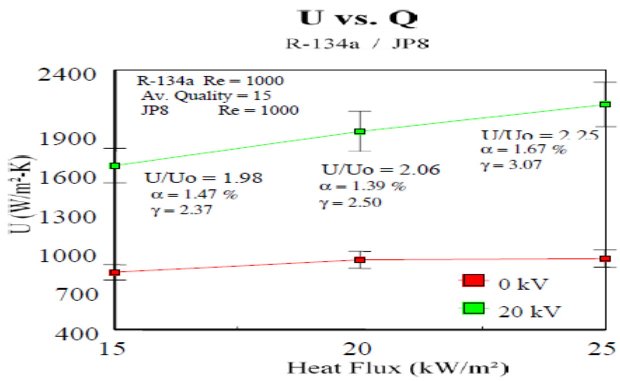

Figure 5.5 5-Port Metallic HX, U vs. Q for R-134a /

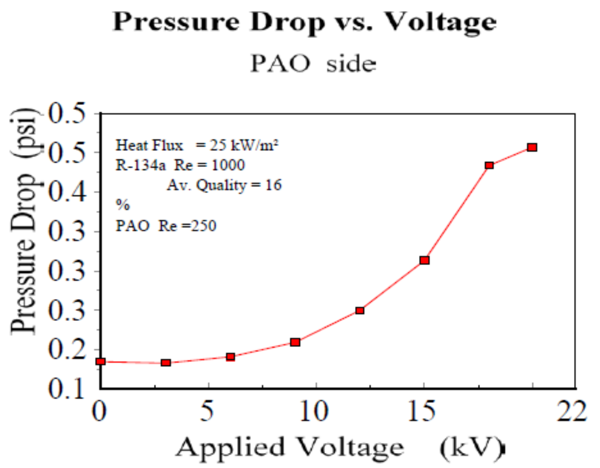

Figure 5.3 5-Port Metallic HX Pressure Drop Trend – Master Base Case

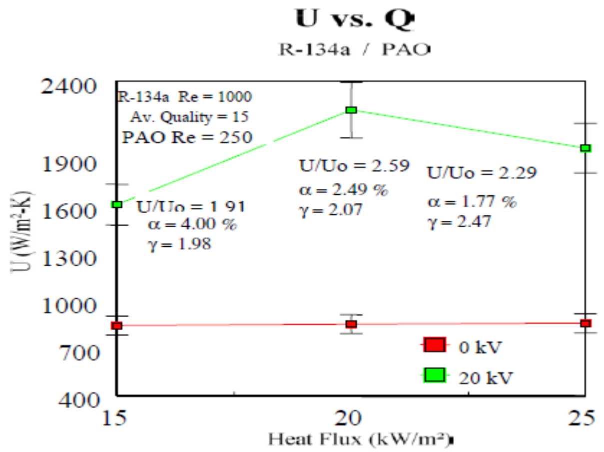

Figure 5.6 5-Port Metallic HX, U vs Q for R-134a / PAO

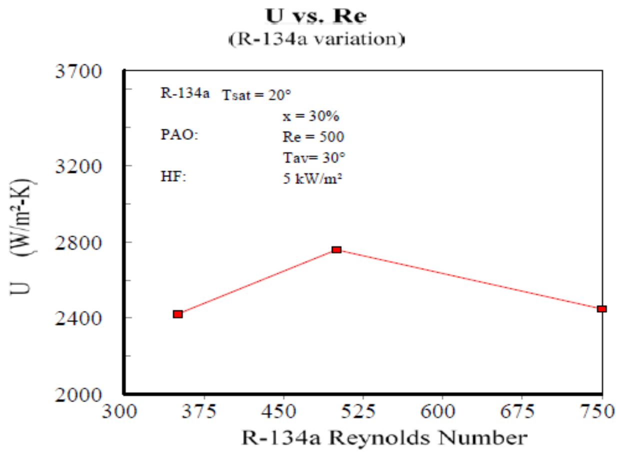

Figure 5.7 Ceramic HX U vs. Refrigerant Re

CONCLUSION

Electrohydrodynamic heat transfer, in this author's opinion, has been proven through this research that it is a viable and technologically sound method to improve heat transfer rates. Improved heat transfer rates will ultimately allow heat exchanger geometries to decrease to sizes more manageable for industries requiring electronic cooling, such as avionics, or other industries where reduced volumes are essential for success. The 5-port metallic, shell and tube heat exchanger described in this paper is already a unit of sufficient capacity to cool fluids using significantly less volume. Additionally, although the ceramic heat exchanger did not produce any enhancement data, the foundation for significant improvement has been laid.
The 5-port metallic, shell and tube heat exchanger, under EHD enhancement, was shown to increase the overall heat transfer coefficient up to 2.6 times using PAO in the enhanced shell side of the heat exchanger. JP8 was shown to increase up to 2.8 fold, also in the shell side. High heat fluxes and low Re flows are shown to be ideal for this technology to succeed. Power consumptions are minimal, especially when compared to high heat flux applications, where they have shown to be as low as 1.4%. The corresponding pressure drop increases, a detriment to any enhancement technology, are comparable to most methods, if not lower. Typically, the pressure drop increases were of the same magnitude as the increase in heat transfer. If additional research requirements such as transient response, power supply packaging, and internal tube enhancement, produced significant success, this particular EHD heat exchanger would be very desirable in almost any commercial technology requiring the reduction of heat loads.

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