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Overview of the innovative heat exchangers technologies

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Abstract. The current paper analyzed the new trends and challenges in heat exchanger technologies. The progress of the studies on mini and micro devices used in industry are presented. Particular attention is paid to the heat exchangers used in marine and chemical industries where the resistance to heat transfer increases due to the fouling or scaling. In the industry, there are very important the reduction in the size of devices, and the micro heat exchangers, due to its variety of advantages offered, are well recognized for their higher performance. The applications of them are ranging from process control to military applications. New engineering approaches for modeling the heat and fluid flow processes in micro heat exchangers are analyzed in the present paper. One of these is based on the dimensional analysis and principles of similitude theory that allow the modeling of microscale systems using a physical system at the mini scale. There are identified constant relationships between dimensions permitting the analysis of the fluid flow through micro channels.

Keywords: heat exchanger, heat transfer intensification, modeling, micro channels

1. Introduction

The need for new types of heat exchangers that could be applied in various areas such as the cooling of electronic devices, bioengineering, advanced energy micro-systems, chemical, medical, defense, aerospace, and automotive applications, etc. provided the opportunity for research on the micro domain where the channel diameter becomes extremely small. Due to the fact that in these industries are very important the reduction in the size of sensors, actuators, and electronic devices, the microsensors for pressure, accelerometers, airbags, "smart" envelopes, navigation, and air conditioning systems, there are frequently used [1]. In the same time, the microtechnologies are applied in production control, in the military application as microdevices for precision-guided munitions, for surveillance, arming systems, data storage sensors, the air traffic control systems, consumer electronics, and office technology, being used in equipment such as tape head driver, inkjet printer heads, earthquake sensors, pressure sensors, data storage systems, optical fiber network components, relays, displays of portables, switches, and filters [3].

Studies on heat transfer at the micro-level began about 40 years [3] by producing and testing a high-performance heat sink with cool water. In the device, the heat generated by microelectronic components is removed by a coolant, flowing through channels, located closer to the heat source. Microchannels have been set at a depth of 300 μm, channel width, and fins of 50 μm in a silicon plate with a thickness of 400 μm. The geometries of the micro heat exchanger have been developed by alternant stacking silicon plates that were tested with water as the working fluid. A heat flux of 790W/cm^2 was measured for an area of 1 cm^2. The temperature difference between thermal agents was 71 °C and the thermal resistance of 0.09 °C/W. The heat flux means the amount of heat that passes through an isothermal surface in unit time.

In recent decades, the use of microchannels in heat exchangers increases their efficiency, lighter devices are made, with smaller dimensions and high compactness. The level of compactness is defined by the ratio between the heat transfer surface and the volume of the heat exchanger. The heat transfer surface plays a key role in the process of heat exchange between two fluids, this being the interface in which heat transfer takes place. The heat transfer speed is directly proportional to the heat transfer surface. The larger the exchange surface, the greater the heat transfer. Increasing the heat transfer surface of a device seems to be an easy way to improve its thermal performance and compact heat exchangers allow maximum surface growth for a minimum volume.

Particular attention is paid to studies related to the thermal characterization of metal foams and their application in industry. The results of research on the design, manufacture, and performance of metal foam heat exchangers are presented in the literature.

Another very interesting approach [4] is that of applying nanofluids in turbulent flows, reporting increased values of the thermal conductivity of nanofluids due to the addition of nanoparticles in the coolant.

Studying the application of nanofluids in turbulent flows, it was found that the thermal conductivity of nanofluids increases by adding nanoparticles to the base fluid, but the convective heat transfer coefficient decreases sometimes and sometimes does not change..

2. Trends and challenges

This chapter provides a brief overview of the technical aspects of trends in the construction of heat exchangers that include both the use of microchannels and metal foams, and the use of nanofluids as working agents.

The problem of using microchannels is not exactly new, but that does not mean that it is not very current. The studies on performances of micro heat exchangers from 1986 [3] highlight that the channel size is 300 μm depth and 400 μm were fabricated using photo-etched corrugated titanium plates technology. The obtained volumetric heat transfer coefficient was higher than 7 MW/m^{3}K and the overall heat transfer coefficients higher than and 4 kW/m^{2}K. In 1988, researchers from the Karlsruhe Nuclear Research Center (CCNK) have been developed in cooperation with the company Messerschmitt-Blohm (MBB), a mechanical method for the manufacture of micro separation nozzle used in the separation nozzle process for isotopes of uranium - 235 enrichment. An important role in this method is playing by the aluminum parts machining that is cutting with high precision micro shaped diamonds [1]. Based on these results, within their activities in the field of micro-technologies, they have developed a new technique for the mechanical manufacture of other microstructures.

Thus, in 1990 a mechanical method for manufacturing microchannels of micro heat exchangers was developed, being generated a model by high precision cutting with profiled micro diamonds, followed by bonding of the foils where these microchannels were made [2], obtaining in this way the micro heat exchanger body. In order to obtain the micro current-flow heat exchanger made by aluminum alloy, copper, stainless steel, and titanium have been used different welding methods such as electron beam welding, diffusion bonding, and laser beam welding. These geometries have been tested with water as the working fluid, and the results were presented for a copper heat exchanger. The results confirm that it is possible to transfer a heat flux of about 20 kW in a volume of 1 cm^3, for a log mean temperature difference of 60 °C.

Channels of 1 cm length and hydraulic diameter of 88 μm have developed a very high volumetric heat transfer coefficient of 234 MW/m3K and an overall heat transfer coefficient of 22.8 kW/m2K, with a pressure drop of 4.7 bar of both water flows [2].

In 1994, Friedrich and Kang have been studied the processing of thin metal foil by cutting with a profiled diamond and their vacuum diffusion bonding for assembling them into a micro counter-flow heat exchanger [6]. They have developed a micro counter-flow heat exchanger made by copper with a channel having a hydraulic diameter of 100μm. The volumetric heat transfer coefficient obtained with this micro heat exchanger was 45 MW/m^3K and the overall heat transfer coefficient was 6 kW/m^2K [1].

Later, in 2001, a group of Chinese researchers has studied fluid flow in microchannels and porous media [4] by forced convection proving that the micro heat exchanger performance using porous media is better than using microchannels, while the pressure drop in the first case is higher. The volumetric heat transfer coefficient for the micro heat exchanger using porous media was 86.3 MW/m^3K, while for the micro heat exchanger using microchannels was 38.5 MW/m^3K. The pressure drops were 4.66 bar for porous medium and 0.7 bar for microchannels. The continuous development of micro-channel heat exchanger technology comes from the requirements of specific process conditions, such as low flow and high operating pressures. Micro-channel tests for plate heat exchangers [5] demonstrate that they withstand pressures greater than 40 bar, while in the case of force-fed micro heat exchanger force- the ability to cool cooling can be cooled up to 925 W/cm^2 with a heat transfer coefficient of 130 kW/m^2K using HFE-7100 refrigerant [6, 7]. The small size of the micro-channels results in more compact heat exchangers and higher heat transfer coefficients due to the increase in surface area per unit volume. Micro-channel heat exchangers can reach the surface per unit volume up to 1500 m^2/m^3 [8].

On the other hand, the development of nanofluid technology has demonstrated the high potential of nanofluids for heat transfer applications, which has led to research in the field of fluid mechanics and, implicitly, in their use in heat exchanger heat agents. The average particle size used in nanofluids can range from 1 to 100 nm. Studies have been performed for both laminar and turbulent flow of thermal agents. An increase in convection heat transfer coefficient was also observed for laminar flow, but turbulent heat transfer is higher for volume fractions of less than 1%, which due to the nature of nanoparticles makes it possible to model single-phase fluid flow. In general, the effects of nanoparticles on the heat transfer coefficient of homogeneous nanofluids are insignificant compared to the effects of the thermophysical properties of nanoparticles in a turbulent flow. According to [8] an increase in the volume fraction of nanoparticles leads to a reduction in the heat capacity of nanofluids. Also, an increase in the volume fraction leads to an increase in viscosity, which leads to an increase in pumping power, which is a challenge in the application of nanofluids. Studies on the increase of heat transfer techniques in the plate, helical, coaxial, tube, and jacket heat exchangers using nanofluids for both single-phase and biphasic heat transfer, as well as for experimental research, are reported [8]. Most empirical and numerical studies indicate that nanofluids have a higher heat transfer coefficient compared to the base fluid, and by increasing the concentration of nanoparticles and turbulence, the performance of heat exchangers will increase, which compensates for the need to increase the heat transfer surface area and therefore reduces the volume of heat exchangers.

Some studies [9] indicate that an increase in the concentration of amorphous carbon nanoparticles in the turbulent working fluid does not lead to any change in the convection heat transfer coefficient, while in the laminar flow, an increase with 8% of the convection heat transfer coefficient, while other studies [9,10] show that the heat transfer coefficient in turbulent flow increases by 26% for volume fractions below 1%, but when the volume fraction is 2%, heat transfer decreases by 14% compared to the base fluid.

In the specialized literature are presented the results of the experimental research carried out on heat exchanger with metal foam [9]. Due to their structural and functional properties, metal foams have stimulated interest in many fields of research and technology [14, 15]. One of the advantages, in the use of metal foams, is the possibility to combine the mechanical properties with the functional properties

[14,15]. Metal foams can be produced can have open or closed-cell structures. This last feature will inevitably define the scope [9]. In particular, closed-cell metal foams are produced by several common methods such as compact powder melting [16,17], or dissolution, and sintering. Replication processes, casting, or coating, can be used to produce open-cell cellular material [9]. A disadvantage is a high cost of producing cellular materials [16]. The particular internal structure of these foams allows the application of these materials in several fields of technologies such as heat exchangers, air-cooled condensers for air conditioning, and refrigeration. Most foams are produced from different metals such as aluminum, copper, nickel, and metal alloys. Heat transfer in metal foams has been studied for practical applications, such as for high porosity fibrous metal foams [17, 18]. As a result, it was concluded that open-cell metal foams can be applied in the construction of heat exchangers because they have high thermal conductivity and flow channels with a complicated geometry that promotes turbulence and, therefore, heat transfer.

3. Conclusions

Studies show that, although the performance obtained with these new technologies is remarkable, one of the major obstacles is their high cost. However, given the performance of these solutions, the need for further field research to study the heat transfer properties of nanofluids in a transient regime, modeling nanofluids as non-Newtonian fluids, and investigating the boiling phenomenon in heat exchangers. It is also expected that further studies on the production of hybrid nanofluids and their application in heat exchangers are needed. As for heat exchangers, in the future, it is necessary to develop some methods for calculating microchannel heat exchangers that take into account of viscous dissipation, temperature drop, and complex boundary layer problems.

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