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Heat Exchangers in Aerospace Applications

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Abstract - *Heat is a form of energy which is transferred when there is a difference in temperature between two or more bodies. In some cases transfer of heat energy can be determined by simply applying the laws of thermodynamics and fluid mechanics. Heat can be transferred by three different means, namely, Conduction, Convection and Radiation. The requirements of thermal management in aerospace applications are continuously growing, whereas the weight and volume requirements of the systems remain constant or shrink. Aerospace systems have high heat flux requirement and it requires compact, high performance and light weight equipment with the capacity to withstand low or no atmospheric pressure. Various experiments and computational methods have been carried out for management of heat transfer and its applications in an aircraft. Although these experiments have not been able to understand the basic mechanism of thermal convection and thermal radiation in space applications. Heat exchangers play a very important role in thermal management of an aerospace system. This paper introduces numerous standard applications of heat exchangers in aerospace systems and presents a few concepts of heat exchangers, which have been used in aerospace or may be thought about as promising designs for aerospace industry.*

***Key Words*: Heat, Heat energy, Thermodynamics, Fluid Mechanics, Conduction, Convection, Radiation, Thermal Management, Aerospace, heat flux, Heat exchangers.**

1. INTRODUCTION

Heat exchangers are equipment being used for transfer of heat between two or more fluids at different temperatures. They are widely used in power plants, auto motives, space heating, refrigeration and air-conditioning systems, aerospace industry, petrochemical processes and electronics cooling. In aerospace industry, heat exchangers are mainly used in three systems: (1) gas turbine cycle, (2) environmental control system (ECS), and (3) thermal management of power electronics. Heat exchangers may be classified in various ways, e.g., based on transfer processes, surface compactness, construction features, flow arrangements, and heat transfer mechanisms. Design and sizing of heat exchangers are generally complicated.

In general, heat transfer, pressure loss, cost, materials, operating limits, size and weight are important parameters. Especially for aerospace industry, the weight and the size of the heat exchanger are most important. Numerous improvement techniques, for example, extended surfaces such as the fins, are used in heat exchangers to enhance the surface area for heat transfer or the heat transfer coefficient, or both. The aim of improvement techniques could be to reduce the size of the heat exchanger for a given function, to increase the capacity of an existing heat exchanger, or to reduce the approach temperature difference. Implementation of heat transfer enhancement techniques in aerospace heat exchangers might help reduce fuel consumption and the size of the heat exchanger.

1. APPLICATIONS OF HEAT EXCHANGERS IN AEROSPACE

2.1. GAS TURBINE CYCLES

Heat exchangers can be implemented in gas turbine cycles to increase thermal efficiency. For a conventional gas turbine cycle, the thermal efficiency mainly depends on the overall pressure ratio and the turbine inlet temperature. The overall pressure ratio indicates the ratio of the compressor outlet pressure to the compressor inlet pressure. The overall pressure ratio and the turbine inlet temperature are limited by the maximum pressure and temperature that the turbine blades can withstand. New materials and innovative cooling concepts for the critical components can further increase the overall pressure ratio and the turbine inlet temperature.

A method to improve the overall pressure ratio for a given compression work is to introduce multistage compression with intercooling, in which the gas is compressed in stages and cooled between each stage by passing the gas through a heat exchanger called an intercooler. Gas turbine engines in aerospace industry require high overall pressure ratio. To achieve higher pressure ratio, the compressor is divided into a low pressure compressor (LPC) and a high pressure compressor (HPC). This is done to introduce an intercooler between LPC and HPC. The compressed gas has a relatively higher temperature at the outlet of LPC. By using a crossflow or counterflow air-to-air heat exchanger, with compressed air flowing on one side and low-temperature ram air flowing on the other side, the compressed air can be cooled before entering the HPC. The steady-flow compression work or the pressure ratio for a given compression work is proportional to the specific volume of the compressed air [8]. The intercooler decreases the temperature and hence decreases the specific volume of the compressed air, which improves the thermodynamic cycle efficiency. In gas turbine engines, the temperature of the exhaust gases leaving the turbine is often considerably higher than that of the air leaving the HPC. A regenerator or a recuperator, i.e. a crossflow or counterflow heat exchanger, can be incorporated to transfer heat from the hot exhaust gases to the compressed air. Accordingly, the thermal efficiency increases because the portion of the energy of the exhaust gases that is supposed to be rejected to the surroundings is recovered to preheat the air entering the combustion chamber. The recuperator is more advantageous when an intercooler is used because a greater potential for recuperation exists. A recuperator is not effective, for highoverall pressure ratios, especially considering its cost, size and weight. Fig 1 shows a conceptual sketch that compares the thermal efficiencies of different gas turbine cycles with the overall pressure ratios. In general, the intercooled and recuperated gas turbine cycle is effective at relatively low overall pressure ratios, e.g. less than 30. The intercooled gas turbine cycle without recuperation is only effective at very high overall pressure ratios. Fig 2 illustrates an intercooled and recuperated gas turbine cycle.

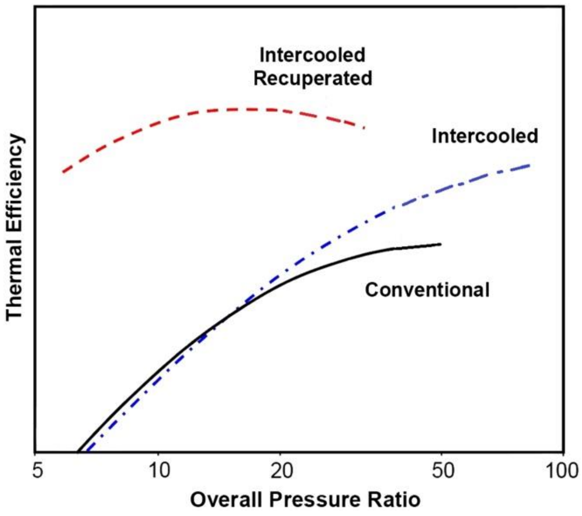

Figure.1 Thermal efficiency versus overall pressure ratio for different gas turbine cycles. Adapted from Sieber J, Overview NEWAC (new aero engine core concepts); April 2009.

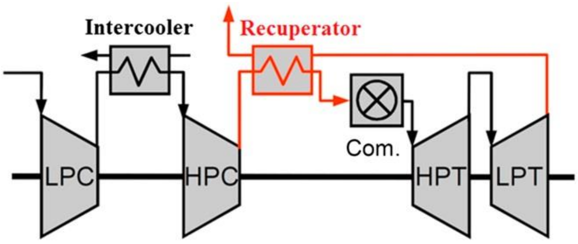

Figure.2 Intercooled and recuperated gas turbine cycle. LPC, low-pressure compressor; HPC, high-pressure compressor; Com, compressor; HPT, high-pressure turbine; LPT, low-pressure turbine Adapted from Sieber J, Overview NEWAC (new aero engine core concepts); April 2009.

In addition, precoolers, such as cryogenic fuel-cooled air heat exchangers, that immediately downstream the air intake to precool the air entering the engine can be used for high-speed jet engines to save fuel consumption for a given overall pressure ratio or to increase the overall pressure ratio for a given compression work. Besides, modern gas turbine engines operate at turbine inlet air temperature levels that are beyond the material maximum temperature. Hence, hot engine components such as the turbine blades must be cooled to assure their structural integrity. Typically the turbine blades are cooled by bleed air from the compressor, which, although cooler than the turbine, has been already heated up by the work done on it by the compressor [8]. Engine bleed reduces thrust and increases fuel burn. The effect is a function of the mass flow rate of the bleed air. If a heat exchanger is used to cool the bleed air before its introduction for blade cooling, the amount of bleed air required by the blade cooling can be reduced, which results in an improved engine performance with a consequent reduction in specific fuel consumption (the rate of fuel consumption per unit of power output). Such a heat exchanger might be a fuel-to-air heat exchanger. The relatively hot bleed air can be cooled by the cool engine fuel. On one hand, the cooling capacity of the bleed air increases as its temperature is decreased. On the other hand, the energy extracted by the fuel is reintroduced into the propulsive cycle as the heated fuel is burned in the combustor.

1.2 ENVIRONMENTAL CONTROL SYSTEM

The ECS is employed in aerospace vehicles such as large commercial aircraft to provide comfortable flight conditions for passengers. There are two kinds of air-conditioning systems on an aircraft: air cycle air-conditioning and vapor cycle refrigeration system. For air cycle air-conditioning, the source of air used by the ECS is typically bleed air from the gas turbine compressor, with a relatively high pressure and temperature. The hot bleed air must first be cooled to an acceptable temperature before entering into the passenger cabin. This is performed using an air-conditioning package that is composed of several units, including a number of heat exchangers cooled by ambient ram air. As shown in Fig. 3 the hot bleed air from the engine compressor is metered through a bleed air valve and then cooled by the primary heat exchanger. Then the air passes to the air cycle machine for pressure adjustment and finally into the secondary heat exchanger for temperature adjustment before entering the cabin. The primary and secondary heat exchangers shown in Fig.3 are air-to-air heat exchangers.

A vapor cycle refrigeration system, in which the refrigerant undergoes phase changes, is basically the same refrigeration cycle that is used in home air conditioners. The vapor cycle refrigeration system is a closed system used for transferring heat from inside the cabin to outside the cabin. Heat exchangers such as evaporators and condensers are important devices in the refrigeration cycle. Specifically the liquid refrigerant decreases its pressure by passing through a thermal expansion valve before entering the evaporator. The liquid refrigerant in the evaporator changes into vapor, absorbing the heat energy from the cabin air. The vapor is then compressed and becomes hot. The hot vapor refrigerant transfers its heat energy to the outside ram air in a condenser and thus the refrigerant condenses back into liquid to repeat the cycle. Therefore, the warm cabin air is constantly replaced or mixed with cool air in the aircraft cabin to maintain a comfortable temperature. An example of a vapor cycle refrigeration system is shown in Fig. 4.

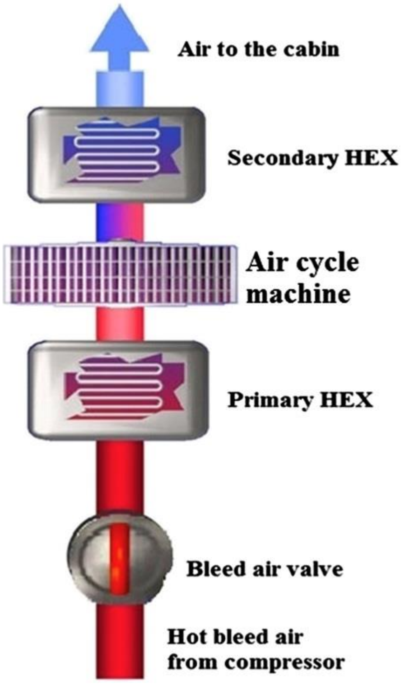

Figure 3 A schematic of an Airbus air-conditioning system [10]. HEX, heat exchanger.

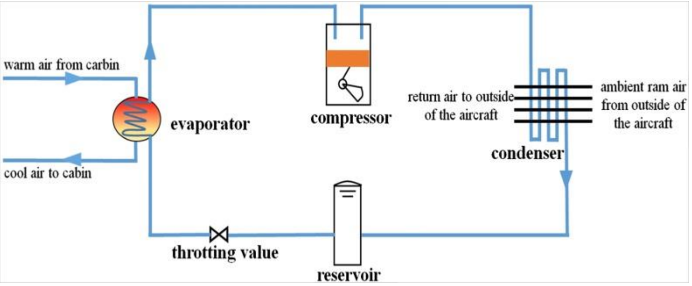

Figure 4 A vapor cycle refrigeration system.

1.3 THERMAL MANAGEMENT

The trend to pack current and future aerospace and military platforms with power-hungry, heat-generating electronic components and systems drives the need for efficient, effective, compact, and lightweight thermal management systems. Shrinking electronics packaging and high-density integration of power electronics to enable more power and functionality in a small unit, coupled with the extremes of military and aerospace environments, constantly place ever-increasing demands on precise and smart thermal management solutions to maintain junction temperatures below levels that degrade performance. The temperature of the components can be maintained at a safe level by air cooling for low-heat-flux components. As the heat flux increases, the limits of air cooling technology are being approached, i.e., forced air heat sinks have become significantly larger, more expensive, and more complex. Liquid cooling is promising to provide the needed level of thermal performance, with an increase in energy efficiency compared to traditional air cooling. The liquid must pass through the heat sources to carry away the heat, resulting in a temperature increase in the liquid. Then the liquid passes through a liquid-to-air heat exchanger, such as a plate-fin heat exchanger (PFHE), to transfer the stored heat to the air. An important component for liquid cooling is the cold plate. The cold plate must be able to dissipate the waste heat efficiently within a relatively small unit. Fig.5 shows examples of cold plates, namely, the tube liquid cold plate and the powdered metal cold plate [11], with the former suitable for low heat fluxes and the latter for high heat fluxes. Cold plates with embedded microchannels are promising to dissipate high heat fluxes. In many cases, heat pipes are embedded in cold plates to increase the effective thermal conductivity of the cold plates. Basically the cold plates should be designed by conforming to the heat-generating components. Besides, the cold plates should be optimized to augment the thermal performance while maintaining a relatively low pressure drop penalty by properly designing, e.g., the liquid flow passages and manifold distributions inside the cold plates. A liquid cooling concept is sketched in Fig.6.

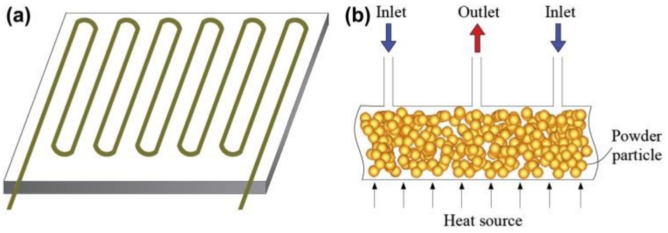

Figure 5 Cold plate examples: (a) a tube liquid cold plate and (b) a powdered metal cold plate.

For ultrahigh heat flux components such as converters or densely packed computing devices with heat fluxes greater than 100 W/cm2, liquid cooling might not be sufficient enough to cool the heat-generating components with certain form factors. Besides, similar to air cooling, liquid cooling cannot provide relatively uniform cooling as the liquid temperature increases along the cooling path. One way of providing an efficient cooling system for high-power-density electronic devices is by using an evaporative cooling circuit. This circuit brings a liquid into thermal contact with the heat-generating components via an evaporating unit to effectively remove heat by utilizing the latent heat of the working fluids and at the same time to maintain a relatively uniform temperature distribution. Compared to air cooling and single-phase liquid cooling, microchannel evaporative cooling has a low pumping power requirement relative to the quantity of heat to be removed [12]. At the same total flow rates, the pressure drop in evaporative microchannels is much higher than that for single-phase liquid flow in conventional channels. However, to dissipate the same amount of heat, much less liquid is required in microchannel evaporative cooling than that in single-phase liquid cooling. Fig.7 shows an evaporative cooling loop with a pump, a cold plate evaporator, an air-cooled condenser, and a reservoir. It has been stated that such an evaporative cooling system with refrigerant R134a as the working fluid can provide twice the cooling capacity in half the size or in a size less than that of air- or water-cooling systems [13].

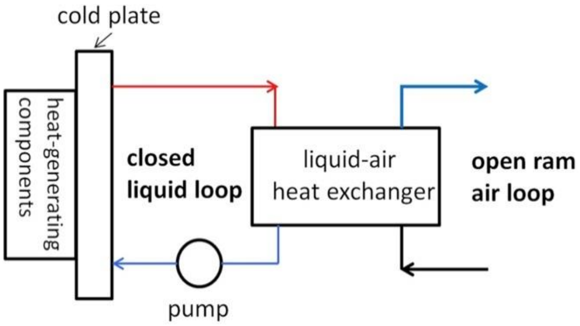

Figure 6 A concept of a liquid cooling solution.

Besides, the temperature of lubricating oil needs to be controlled. The excessive heat caused by friction in devices such as gearboxes and compressors increases the lubricant oil temperature. As the oil viscosity decreases with increment in temperature, the lubricant oil film becomes thinner and collapses, which in turn causes more friction and heat. Fuel or ambient ram air can be used as working fluids in fuel-cooled oil cooler or air-cooled oil cooler to cool the lubricants.

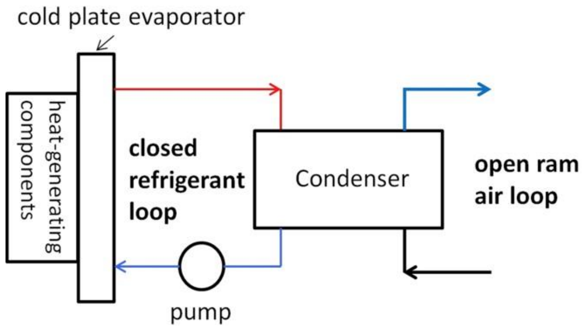

Figure 7 An exemplified evaporative cooling system.

3. GENERAL DESIGN CONSIDERATIONS FOR AEROSPACE HEAT EXCHANGERS

The typical features of aerospace heat exchangers are briefly listed below.

- Compactness and lightweight: Compact heat exchangers are promising because of the limited space available for heat transfer in aerospace industry. Light materials such as aluminum alloy and metal foam might be preferred if the operating pressure and temperature are less than the maximum allowable pressure and temperature of the materials.

- Relatively high temperature and pressure for some aerospace heat exchangers such as recuperators: Compressed air leaving the HPC flows on one side of the recuperator and the exhaust gas exits from the turbine flows on the other side. For example, for an overall pressure ratio of 50, the compressed air leaving the HPC has a pressure of 50 bar and a temperature up to 1000 K. The materials for high-temperature heat exchangers should be able to maintain structural integrity to cope with large temperature differences.

- High effectiveness and minimum pressure loss: The heat-exchanging surfaces and flow paths should be designed in such a way to give a high thermal conductance with a minimum pressure loss. Besides, the bypass duct and the inlet and outlet ducts to and from the heat exchangers need to be arranged properly to minimize momentum pressure losses.

4. TYPES OF HEAT EXCHANGERS

4.1 PLATE-FIN HEAT EXCHANGERS

A PFHE consists of flat plates and finned chambers to transfer heat between fluids. PFHE is often categorized as a compact heat exchanger with a relatively high heat transfer surface area to volume ratio. In aerospace industry, aluminum alloy PFHEs have been used for 50 years for their compactness and lightweight properties. Most commonly this heat exchanger type is for gas-to-gas heat exchange. Various fin geometries such as triangular, rectangular, wavy, louvered, perforated, serrated, or the so-called offset strip fins are used to separate the plates and create the flow channels. The common fin thickness ranges from 0.046 to 0.20 mm and the fin height ranges from 2 to 20 mm.

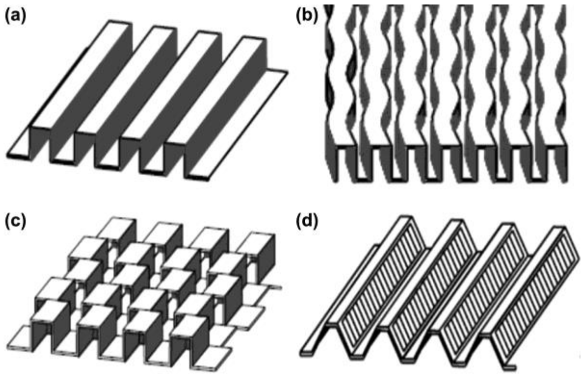

Figure 9. Types of fin geometries: (a) rectangular fin, (b) wavy fin, (c) offset strip fin, and (d) louvered fin.

4.2 PRINTED CIRCUIT HEAT EXCHANGERS

The concept of PCHEs was first invented in the early 1980s at the University of Sydney in Australia. It has been commercially manufactured by Heatric Ltd in the United Kingdom since 1985. A brief introduction of PCHE is given in Reay et al. [4]. The PCHE derives its name from the procedure used to manufacture the plates that form the core of the heat exchanger; the fluid flow passages are produced by chemical milling, a technique similar to that used to manufacture printed circuit boards in the electronics industry. A benefit of this design is the flexibility it affords in terms of flow passage geometry. The fluid flow passages for PCHE have approximately a semicircular cross section. Channel depths and channel widths are typically in the range 0.5–2.0 mm and 0.5–5.0 mm, respectively, and may be larger for some streams. PCHEs are highly compact because of their high surface area-to-volume ratios (>2500 m2/m3) [15]. A PCHE is a high-efficiency plate-type compact heat exchanger, which is typically four to six times smaller and lighter than a shell-and-tube heat exchanger of equivalent performance.

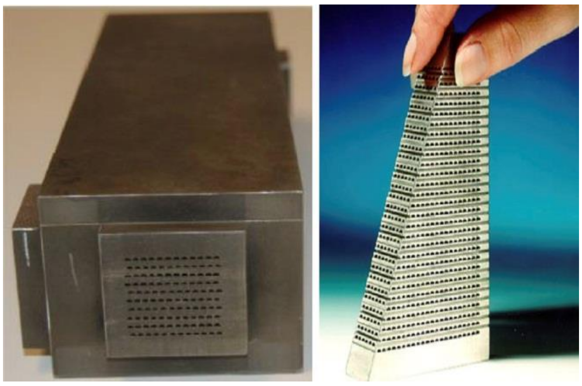

Figure 10. A diffused PCHE

4.3 MICRO HEAT EXCHANGERS

Micro- and miniscale heat exchangers (μHEXs) are heat exchangers in which at least one fluid flows in lateral confinements such as channels or small cavities with dimensions less than around 1 mm in size. Some PFHEs and PCHEs can also be categorized as μHEXs. Typically, the fluid flows through a cavity that is called a microchannel. This process intensification technology exploits heat transfer enhancement resulting from structurally constrained fluid streams in microchannels, which reduces the thermal resistance considerably. Micro heat exchangers have been demonstrated with high heat transfer coefficients, approximately one order of magnitude higher than the typical values of conventional heat exchangers. Therefore, as a typical miniaturized process device, micro heat exchangers have attracted widespread applications because of their high thermal performance, compactness, small size, and lightweight [20], with the aim of process intensification. Micro heat exchangers are used in diverse energy and process applications such as electronics cooling, automotive and aerospace industries, chemical process intensification, refrigeration and cryogenic systems, and fuel cells. Micro heat exchangers have many advantages over conventional heat exchangers. First, in the scaling down from macro- to microscale, the volume decreases with the third power of the characteristic linear dimensions, whereas the surface area only decreases with the second power. Therefore, micro heat exchangers have relatively larger surface area-to-volume ratios that enable higher heat transfer rates than conventional heat exchangers. Second, fast fluid acceleration and close proximity of the bulk fluid to the wall surface in μHEXs give high heat transfer coefficients. For single-phase fully developed internal laminar flow, a constant Nusselt number (Nu = hdh/k) implies that the single-phase heat transfer coefficient increases as the hydraulic diameter decreases. In addition, compactness and high heat-flux dissipation are required as the scale of the devices decreases, whereas the power density increases. Micro heat exchangers are expected to manage the high heat-flux dissipation for miniaturized devices to guarantee the reliability and safety during operation.

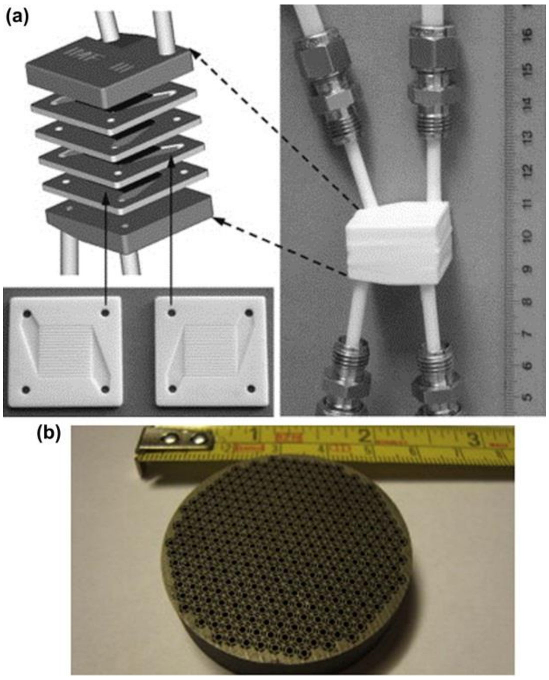

Figure 11. Examples of micro heat exchangers: (a) ceramic micro heat exchanger [24] and (b) 3D-printed heat exchanger by Sustainable Engine Systems Ltd. [4].

5. OTHER AEROSPACE HEAT EXCHANGERS

5.1 PRIMARY SURFACE HEAT EXCHANGERS

Primary surface heat exchangers refer to heat exchangers wherein substantially all the material that conduct heat between two media comprises the walls separating the two media. This type of heat exchangers primarily consists of plates or sheets and have no separate or additional internal members, such as fins, so that the exchanger is constructed of plates or sheets, each side of which is in contact with a different fluid, and heat transfer occurs substantially and directly between the plates and the fluid. In contrast, extended surface heat exchangers, or secondary surface heat exchangers, contain a substantial amount of material in the form of fins, which do not separate the media. The PFHE and micro heat exchanger are mostly extended surface heat exchangers. The main attributes of primary surface heat exchangers are that the surface geometry is 100% effective (no fins) and sealing can be accomplished by welding without the need for an expensive and time-consuming high-temperature furnace brazing operation. Primary surface heat exchangers can be used as intercoolers and recuperators in the aerospace industry.

5.2 HEAT PIPE HEAT EXCHANGER

Heat pipes of various capillary wick structures are attractive in the area of spacecraft cooling and temperature stabilization because of their lightweight, zero maintenance, and reliability. A heat pipe consists of an evaporation zone, an adiabatic zone, and a condensation zone. Liquid in contact with the evaporation zone turns into vapor by absorbing heat, and vapor then travels along the heat pipe to the condensation zone and condenses back into liquid, releasing the latent heat. The liquid then returns to the evaporation zone through capillary forces or other external forces. Loop heat pipes and micro/miniature heat pipes are promising types suitable for cooling solutions. Micro heat pipes are heat pipes with a height less than about 1 mm. Micro and miniature heat pipes are able to dissipate high heat fluxes up to 100 W/cm2 [29]. A major advantage of heat pipes is that no external power is required. For high heat fluxes, heat pipes need a relatively larger area for heat dissipation from the heat pipe condensation zone to the environment, which might be a concern because of the limited space in aerospace. The depth of the micro heat pipe is less than 1.0 mm. The width and the length of the evaporation zone depend on the form factor of the electronic components. The length of the condensation zone can be designed by the required dissipated heat and the cooling mode of the external heat sink.

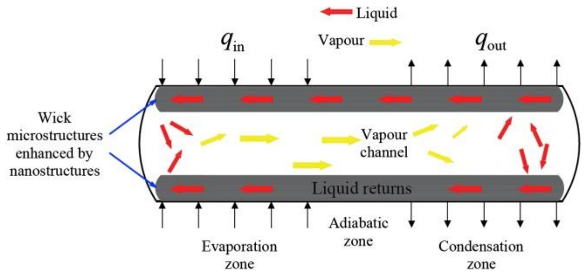

Figure 12. A flat micro heat pipe.

6. HEAT EXCHANGERS USING NEW MATERIALS

6.1 FOAM MATERIALS

Light materials are preferred in the manufacturing of aerospace heat exchangers to save fuel consumption. Aluminum alloy heat exchangers such as aluminum alloy PFHEs are common in the aerospace industry. Foam materials such as open-cell porous metallic foams and graphite foams have received increased attention for use in commercial heat exchangers because of their lightweight, improved thermal performance, high compactness, attractive flexibility to be formed in complex shapes, good stiffness/strength properties, and low cost via the metal sintering route for mass production, as well as because some materials can be used at high temperatures up to 1200 K. Because of the interconnection of pores and tortuosity of open-cell foams, fluid mixing and convection heat transfer are greatly enhanced. The key parameters that influence the thermohydraulic performance of foams are porosity, pore density (pores per inch), mean pore diameter, surface area-to-volume ratio, effective thermal conductivity, and permeability. The pertinent correlations for flow and thermal transport in metal foam heat exchangers were categorized in Ref. [30] Graphite foam is attractive, as the density of graphite foam ranges from 200 to 600 kg/m3, which is about 20% of that of aluminum. However, the tensile strength of graphite foam is much less than that of metal foam. The weak mechanical properties of graphite foam block its development as a heat exchanger. Adding more material into the graphite foam or changing the fabrication process might improve the mechanical properties of the foam [31]. The major disadvantage of open-cell foams is the relatively high pressure drop penalty, as pointed out by Muley et al. [32]. Besides, at present, foam heat exchangers are not suitable for high-pressure conditions, as the maximum pressure for foam heat exchangers is relatively low.

6.2 CERAMIC MATERIALS

The two main advantages of using ceramic materials and ceramic matrix composites (CMCs) in heat exchanger construction over traditional metallic materials are their temperature resistance and corrosion resistance. Ceramics and CMCs are now used in rocket nozzles and jet engines, heat shields for space vehicles, aircraft brakes, gas turbines for power plants, fusion reactor walls, heat treatment furnaces, heat recovery systems, etc. Major obstacles preventing the wide use of ceramics include ceramic-metallic mechanical sealing, manufacturing costs and methods, and their brittleness in tension. The most commonly used CMCs are non-oxide CMCs, i.e., carbon/carbon, carbon/silicon carbide, and silicon carbide/silicon carbide. At present, various heat exchangers, such as PFHEs, micro heat exchangers, and primary surface heat exchangers, can be manufactured by ceramics. Ceramic recuperators and intercoolers can be used to improve the gas turbine cycle efficiency.

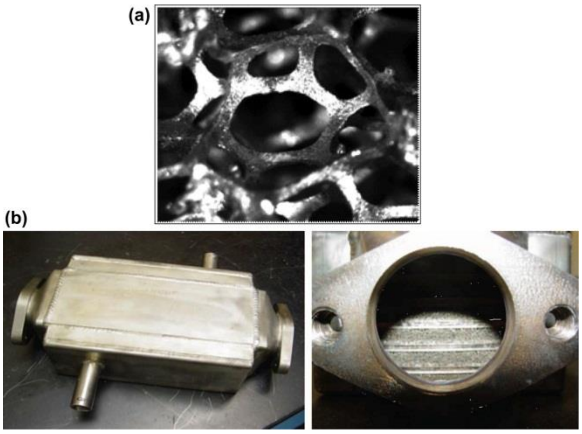

Figure 13. (a) Open-cell metal foam and (b) a foam heat exchanger [32].

7. CONCLUSION

Aerospace heat exchangers are mainly used in gas turbine cycles, ECSs, and thermal management of various aerospace systems. The applications of aerospace heat exchangers are discussed. The main features are listed for aerospace heat exchangers. This paper also illustrates various typical compact heat exchangers including PFHEs, micro heat exchangers, PCHEs, primary surface heat exchangers, and heat pipes, which are favorable to provide efficient heat transfer and cooling in the aerospace industry.

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