Enhancing Heat Transfer in Compact Heat Exchangers for Aerospace Applications

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Application of the Project:

This project aims to improve the efficiency of heat exchangers used in aerospace applications, which could lead to significant energy savings and improved performance of aerospace vehicles.

Motivation of the Project:

With the increasing demand for energy-efficient and high-performance aerospace vehicles, there is a pressing need to enhance the heat transfer capabilities of compact heat exchangers used in these applications.

Important Questions to be Addressed:

- Engineering Significance: What methods can be employed to enhance the heat transfer efficiency of compact heat exchangers to satisfy the stringent needs of aerospace applications?
- Scientific Significance: What are the fundamental heat transfer processes within compact heat exchangers, and how can these be tailored for conditions specific to aerospace applications?

Relevance of Continuum Mechanics and Transport Phenomenon:

CMTP principles are crucial for understanding the behavior of fluids and heat transfer processes in heat exchangers. The aspects of CMTP relevant to this project include fluid dynamics and heat transfer.

Emphasis of our Project:

The project will primarily focus on investigating and applying various heat transfer enhancement techniques to improve the performance of compact heat exchangers used in aerospace applications.

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 Terms:

- Heat Exchanger: A device used to transfer heat between two or more fluids.
- Heat Transfer Coefficient: A measure of the heat transfer between a solid surface and a fluid per unit temperature difference.
- Compact Heat Exchanger: A type of heat exchanger designed to allow a large heat transfer surface area per unit volume.

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.

Balance Equations:

The governing equations for this project would be the conservation of mass, momentum, and energy. These are also known as the Navier-Stokes equations and the energy equation.

❖ Conservation of Mass (Continuity Equation):

In fluid dynamics, the continuity equation states that the rate at which mass enters a system is equal to the rate at which mass leaves the system plus the accumulation of mass within the system. The differential form of the continuity equation is:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

where

- ρ is fluid density,
- t is time,
- $\mathbf{u}$ is the flow velocity vector field.

Source: https://en.wikipedia.org/wiki/Continuity_equation

The time derivative can be understood as the accumulation (or loss) of mass in the system, while the divergence term represents the difference in flow in versus flow out. In this context, this equation is also one of the Euler equations (fluid dynamics). The Navier–Stokes equations form a vector continuity equation describing the conservation of linear momentum.

If the fluid is incompressible (volumetric strain rate is zero), the mass continuity equation simplifies to a volume continuity equation:

$$\nabla \cdot \mathbf{u} = 0,$$

which means that the divergence of the velocity field is zero everywhere. Physically, this is equivalent to saying that the local volume dilation rate is zero, hence a flow of water through a converging pipe will adjust solely by increasing its velocity as water is largely incompressible.

❖ Conservation of Momentum (Navier-Stokes Equation):

The Navier–Stokes momentum equation can be derived as a particular form of

$$\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} = \frac{1}{\rho}\nabla \cdot \boldsymbol{\sigma} + \mathbf{g}.$$

the Cauchy momentum equation, whose general convective form is

Cauchy momentum equation *(convective form)*

$$\rho \frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho \mathbf{g}$$

where

- $\frac{\mathrm{D}}{\mathrm{D}t}$ is the material derivative, defined as $\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla$,
- ρ is the (mass) density,
- $\mathbf{u}$ is the flow velocity,
- $\nabla \cdot$ is the divergence,
- p is the pressure,

Source: https://en.wikipedia.org/wiki/Navier%E2%80%93Stokes_equations#General_continuum_equations

By setting the Cauchy stress tensor to be the sum of a viscosity term (the deviatoric stress) and a pressure term (volumetric stress), we arrive at:

In this form, it is apparent that in the assumption of an inviscid fluid – no deviatoric stress – Cauchy equations reduce to the Euler equations.

Assuming conservation of mass we can use the mass continuity equation (or simply continuity equation),

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\, \mathbf{u}) = 0$$

to arrive at the conservation form of the equations of motion. This is often written:

Cauchy momentum equation *(conservation form)*

$$\frac{\partial}{\partial t}(\rho\, \mathbf{u}) + \nabla \cdot (\rho\, \mathbf{u} \otimes \mathbf{u}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho\, \mathbf{g}$$

where $\otimes$ is the outer product:

$$\mathbf{u} \otimes \mathbf{v} = \mathbf{u}\mathbf{v}^{\mathrm{T}}.$$

Source: https://en.wikipedia.org/wiki/Navier%E2%80%93Stokes_equations#General_continuum_equations

The left side of the equation describes acceleration, and may be composed of time-dependent and convective components (also the effects of non-inertial coordinates if present). The right side of the equation is in effect a summation of hydrostatic effects, the divergence of deviatoric stress and body forces (such as gravity).

❖ Conservation of Energy (Energy Equation):

The equation for energy conservation, also recognized as the First Law of Thermodynamics, outlines the transfer and transformation of energy within a system. Depending on the specific context and assumptions, it can be represented in different ways. Generally, the equation is formulated as follows:

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot (\rho \mathbf{u} E) = \nabla \cdot (\mathbf{q} - p\mathbf{u}) + \nabla \cdot (\tau \cdot \mathbf{u}) + \rho \mathbf{g} \cdot \mathbf{u} + Q$$

Here, the terms represent:

- ρ: Density of the fluid.
- E: Total energy per unit volume, including internal energy, kinetic energy, and potential energy.
- t: Time.
- $\mathbf{u}$: Velocity vector.
- ∇: Del operator (gradient operator).
- $\cdot$: Dot product.
- $\mathbf{q}$: Heat flux vector.
- p: Pressure.
- τ: Stress tensor.
- $\mathbf{g}$: Gravitational acceleration.
- Q: Heat source/sink term.

Source: Wikipedia

This equation fundamentally asserts that the variation in total energy within a control volume is equivalent to the sum of energy entering and exiting, energy added or removed due to work performed by pressure and viscous forces, energy gained or lost due to gravitational influences, and any heat produced or absorbed within the system.

Constitutive Relations:

The constitutive relations for this project would involve the properties of the materials used in the heat exchangers, such as thermal conductivity, density, and specific heat capacity. These properties can be related to temperature through empirical relations or approximated as constants for small temperature ranges.

For example, the thermal conductivity:

$$k = k_0(1 + \alpha(T - T_0))$$

- k: Thermal conductivity
- k_0: Reference thermal conductivity
- α: Temperature coefficient of thermal conductivity
- T: Temperature
- T_0: Reference temperature

Heat transfer Coefficients at interfaces(h):

$$h = \frac{k}{\delta}$$

- h: Heat transfer coefficient
- k: Thermal conductivity
- δ: Characteristic length

Important Considerations to obtain solutions:

a. Assumptions:

- Steady-state conditions: The system's properties are assumed to remain constant over time, simplifying the analysis.
- Incompressible flow: The fluid's density is assumed to be constant, a valid assumption for many aerospace applications.
- Negligible radiation effects: It's assumed that radiative heat transfer is minimal compared to convective and conductive heat transfer.

b. Boundary Conditions:

- Inlet temperatures, pressures, and flow rates: Accurate specification of these conditions is essential for precise simulations and experiments.

c. Material Properties:

- Accurate determination of properties like thermal conductivity and specific heat is crucial for reliable heat transfer predictions.

d. Flow Regimes:

- Identifying flow regimes (e.g., laminar, turbulent, two-phase flow) within the heat exchanger is vital for choosing the right correlations and models.

Result:

a. Comparative Analysis:

- Detailed comparison of heat transfer performance between traditional and improved compact exchanger designs under various conditions.

b. Heat Transfer Enhancement Factor:

- Measurement of the increase in heat transfer efficiency achieved through the proposed enhancements.

c. Flow Visualization:

- Visual depiction of flow patterns and phase distribution within the heat exchanger, assisting in understanding the fluid dynamics involved.

d. Temperature Distributions:

- Contour plots of temperature fields to visualize heat transfer profiles and pinpoint areas of high or low performance.

Conclusions Drawn from Results:

a. Performance Improvement:

- The suggested enhancements result in a significant boost in heat transfer efficiency, confirming the effectiveness of the changes.

b. Impact of Multiphase Flow:

- Multiphase flow behavior and phase change phenomena play a crucial role in optimizing heat transfer performance, emphasizing the importance of CMTP principles.

c. Practical Applicability:

- The results show the feasibility and potential advantages of using advanced materials and design changes in aerospace heat exchangers.

Key Takeaway:

The research provides compelling evidence that the use of advanced materials and optimized design configurations can significantly improve aerospace heat exchanger performance. This addresses the urgent need for higher efficiency in aerospace systems and paves the way for future advancements in compact heat exchanger technology across various sectors. The success of the study underscores the importance of ongoing innovation in heat transfer research for aerospace applications.

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