Conductive heat transfer analysis on Brass and Helium interface using Ansys

AE-608: Heat Transfer for Aerospace Applications

Term Project Report

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Contents

1 Objective

The objective of this project is to conduct a thorough conduction-based thermal analysis of a system composed of brass and helium. This analysis aims to investigate the heat transfer rate and temperature distribution between the brass material and helium. The study is crucial for understanding the thermal behavior of such systems, which can have applications in various engineering fields, including aerospace, Climate Control Systems, and industrial processes. The analysis is performed using Ansys commercial software, renowned for its capabilities in simulating complex thermal phenomena accurately.

2 Introduction

Conduction is a fundamental process in physics and thermodynamics that describes the transfer of heat through a material without any noticeable movement of the material itself. It occurs when there is a temperature difference between two regions of a substance, causing energy to flow from the hotter region to the colder region. Understanding conduction allows scientists, engineers, and designers to develop technologies that efficiently transfer heat, leading to innovations in various fields and enhancing our daily lives. The mechanism of conduction involves the transfer of energy between adjacent molecules or electrons within a material. In solids, which are the primary medium for conduction, molecules are closely packed together, allowing them to interact strongly through intermolecular forces.

In everyday life, it exhibits in various ways and plays a crucial role in numerous applications, some are Thermal Comfort: when we touch a cold surface, heat is conducted away from our bodies, Home Insulation: for maintaining comfortable indoor temperatures and reducing energy costs, Food Preparation: Heat is conducted from the heat source to the cooking vessel, and then to the food, causing it to cook, Electrical Systems:Metals like copper and aluminum, with high electrical conductivity, are used in wiring to efficiently transmit electricity, Material Selection: in aerospace engineering, materials with low thermal conductivity are preferred for insulating spacecraft from extreme temperatures, Climate Control Systems: Conduction influences the design and operation of heating, ventilation, and air conditioning (HVAC) systems. Medical Devices: In healthcare, conduction is utilized in medical devices such as thermometers, heating pads, and cooling blankets.

3 Thermal conduction

The fundamental equation governing thermal conduction is the heat conduction equation [2]. It describes how temperature changes over time and space within a material due to heat transfer. To solve the heat conduction equation, boundary conditions and initial conditions must be specified. Boundary conditions define the temperature distribution or heat flux at the boundaries of the material, while initial conditions specify the initial temperature distribution within the material at t=0.

Fourier's Law of Heat Conduction: Fourier's Law of Heat Conduction is a fundamental principle that relates heat flux (q'') to the temperature gradient (∇T) in a material. Mathematically, it is expressed as:

$$q'' = -k\nabla T$$

Three-dimensional heat conduction equation, is a fundamental partial differential equation governing the transfer of heat within three-dimensional objects.

$$q'' = -k\Delta T = -k\left(\frac{\partial T}{\partial x}i + \frac{\partial T}{\partial y}j + \frac{\partial T}{\partial z}k\right) \tag{1}$$

Heat Flux (q''):

This represents the heat flux vector. Heat flux (q'') is the rate of heat transfer per unit area and is measured in watts per square meter (W/m²). It indicates the amount of heat energy flowing through a surface per unit time.

Thermal Conductivity (k):

k is the thermal conductivity of the material through which heat is being conducted. Thermal conductivity (k) is a material property that quantifies how easily heat can flow through a material. It is measured in watts per meter per kelvin (W/mK).

Temperature Gradient Component ($\frac{\partial T}{\partial x}i + \frac{\partial T}{\partial y}j + \frac{\partial T}{\partial z}k$):

This part represents the gradient of the temperature field T in three dimensions.

$\frac{\partial T}{\partial x} i$ represents the rate of change of temperature in the x-direction (with respect to the spatial coordinate x) multiplied by the unit vector i in the x-direction. Similarly, $\frac{\partial T}{\partial y} j$ and $\frac{\partial T}{\partial z} k$ represent the rate of change of temperature in the y-direction and z-direction, respectively.

The gradient of temperature (∇T) indicates how temperature changes with respect to spatial coordinates. In this case, it's decomposed into three components along the x, y, and z axes.

Temperature Gradient Vector (∇T):

This part represents the vector sum of the temperature gradients in the x, y, and z directions. It's a vector quantity that indicates both the magnitude and direction of the temperature gradient.

The negative sign before k indicates that heat flows from regions of higher temperature to regions of lower temperature, in accordance with the second law of thermodynamics.

Overall Equation:

The equation states that the heat flux (q'') is equal to the negative product of the thermal conductivity (k) and the temperature gradient vector (∇T). This relationship expresses Fourier's Law of Heat Conduction, which describes how heat is conducted through a material in response to a temperature gradient.

4 Simulation setup

ANSYS Fluent [3] is a widely used software in Computational Fluid Dynamics (CFD) for simulating and analyzing fluid flows and heat transfer phenomena. It offers a comprehensive suite of tools for solving complex fluid dynamics problems encountered in various engineering fields such as aerospace, automotive, chemical, and biomedical engineering. With its advanced modeling capabilities, Fluent allows engineers and researchers to simulate a wide range of flow scenarios, including laminar and turbulent flows, multiphase flows, combustion, and heat transfer. The software provides a user-friendly interface combined with powerful solver algorithms, enabling users to set up, solve, and analyze CFD simulations efficiently. Additionally, Fluent offers robust post-processing capabilities for visualizing and interpreting simulation results, aiding in the design optimization process. Its versatility and accuracy make ANSYS Fluent a go-to tool for engineers and researchers worldwide in predicting fluid flow behavior, optimizing designs, and solving real-world engineering challenges.

4.1 Governing equation

Fluent solves energy equation numerically to predict temperature distributions, heat transfer rates, and overall thermal behavior of the system [1]. This equation accounts for the conservation of energy within the fluid flow, considering various factors such as convection, diffusion, and energy generation. The equation tracks the rate of change of total enthalpy with respect to time, including contributions from kinetic and internal energy. The divergence of the total enthalpy flux captures the transport of energy through the flow field.

Energy Equation

$$\frac{\partial}{\partial t}(\rho h_t) + \frac{\partial}{\partial x_j}(\rho h_t u_j) = \frac{\partial P}{\partial t} + \frac{\partial}{\partial x_j}\left(u_i \tau_{ij} + \lambda \frac{\partial T}{\partial x_j}\right) \tag{2}$$

$\frac{\partial}{\partial t}(\rho h_t)$: Rate of change of total enthalpy (h_t) with respect to time.

$\frac{\partial}{\partial x_j}(\rho h_t u_j)$: Divergence of the total enthalpy flux $(\rho h_t u_j)$.

$\frac{\partial P}{\partial t}$: Rate of change of pressure (P) with respect to time.

$\frac{\partial}{\partial x_j}(u_i \tau_{ij} + \lambda \frac{\partial T}{\partial x_j})$: Divergence of the sum of viscous and conductive heat fluxes.

Shear Stress Tensor

$$\tau_{ij} = 2\mu \left[\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \frac{1}{3}\delta_{ij}\frac{\partial u_i}{\partial x_j}\right] \tag{3}$$

μ : Dynamic viscosity.

δ_{ij} : Kronecker delta.

u_i : Velocity component in the i-th direction.

Total Enthalpy

$$h_t = h + \frac{1}{2}(u_i^2) \tag{4}$$

4.2 Grid Independent test

In the ANSYS Fluent setup, coarse, medium and fine meshes have been chosen. The comparison between medium and fine was a really agreeable amount so due to computational expensive the medium mesh has been chosen shown in figure 1. the computational domain comprises 174,859 cells, 355,871 faces, and 32,401 nodes.

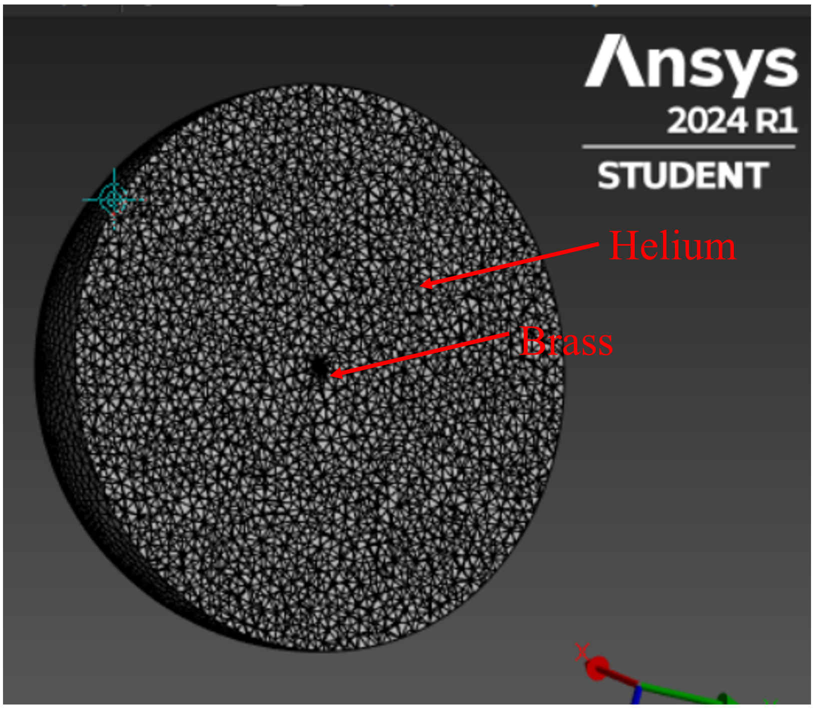

Figure 1: Grid of Brass and Helium

configured for three-dimensional analysis. The simulation is set for unsteady time-dependent calculations using a second-order implicit scheme. The flow is assumed to be laminar, neglecting turbulent effects. The governing equations for both flow and energy transport are activated. Pressure-velocity coupling is implemented using a coupled approach, while the flow Courant number is set to 200 to ensure numerical stability. For discretization, a second-order scheme is employed for pressure, momentum, and energy equations, with momentum discretized using a second-order upwind scheme, and energy discretized using a second-order upwind scheme as well. These settings collectively govern the computational solution process within ANSYS Fluent, enabling accurate prediction of flow and thermal behavior within the defined domain.

5 Initial and Boundary Conditions

Initial and boundary conditions are essential components of mathematical models used in numerical simulations to solve differential equations. In the context of thermal analysis or computational fluid dynamics (CFD), these conditions define the starting point and the behavior at the boundaries of the computational domain. Initial conditions specify the values of the variables of interest (e.g., temperature, velocity) at the beginning of the simulation or at t=0. These conditions are necessary because most simulations involve solving time-dependent partial differential equations (PDEs), and the solution evolves over time. Boundary conditions specify the behavior of the variables of interest at the boundaries of the computational domain. They define how the variables interact with the external environment or other parts of the system.

Conditions	value
Solid Initial Temperature	900 K
Fluid Initial Temperature	200 K
Wall Motion	Stationary Wall
Shear Boundary Condition	No Slip

Table 1: Initial and Boundary Condition

6 Material Selection

In the current work, the solid(Brass) has been chosen which is kept at 900K and the enclosure is filled with Fluid (Helium) which is at a temperature of 200K. Brass is a metallic alloy made primarily of copper (Cu) and zinc (Zn), although other elements can be added to modify its properties. It has been used by humans for thousands of years and holds a significant place in history due to its versatility, durability, and aesthetic appeal. Brass exhibits good strength and ductility, making it easy to form into various shapes. It is often preferred for applications requiring intricate designs or detailed components. it also has excellent corrosion resistance in most environments, particularly to atmospheric and water corrosion. This property makes it suitable for use in plumbing, marine hardware, and outdoor applications. Brass is highly machinable, allowing it to be easily shaped, drilled, and turned on lathes. Brass exhibits good thermal conductivity, allowing it to efficiently transfer heat. It also has excellent electrical conductivity, nearly as high as pure copper.

Specifications	value
Diameter	10 mm
Density	8711.6 kg/m^3
Cp (Specific Heat)	382.32 J/(kg K)
Thermal Conductivity	192 W/(m K)

Table 2: Brass material property

Helium is a fascinating element, known for its unique properties and diverse range of applications. Helium is a chemical element with the symbol He and atomic number 2. It's the second lightest and second most abundant element in the observable universe, after hydrogen. It has the lowest boiling and melting points of all the elements. It remains liquid at temperatures close to absolute zero. Also it is one of the least dense elements. It's about one-seventh the density of air, which makes it rise in air. it has the highest thermal conductivity of any element, making it useful in cooling applications. At very low temperatures, helium exhibits remarkable properties, such as superfluidity. Superfluid helium can flow without friction, and it behaves as if it has zero viscosity. Other important applications are cryogenics, Welding and leak Detection, balloons and airships, deep-Sea Diving, space Exploration, medical applications.

Specifications	value
Diameter	1000 mm
Density	0.1625 kg/m^3
Cp (Specific Heat)	5193 J/(kg K)
Thermal Conductivity	0.152 W/(m K)
Viscosity	1.99e-05 kg/(m s)
Molecular Weight	4.0026 kg/kmol

Table 3: Helium material property

7 Results and discussion

7.1 Total heat transfer rate

The source material, Brass, is characterized by high temperatures, resulting in a rapid rate of heat transfer at the initial stage. This high rate of heat transfer is primarily due to the stark temperature differential between the Brass and its surroundings. As heat naturally moves from regions of high temperature to low temperature, the relatively cooler fluid, Helium, begins to come into contact with the Brass.

As the Helium interacts with the Brass, absorbing heat from it, the rate of heat transfer gradually decreases. This decrease is visually represented in Figure 2, where a declining trend in heat transfer rate becomes evident.

Initially, the steep slope of the curve indicates a rapid decrease in the rate of heat transfer as the Helium absorbs thermal energy from the Brass.

Initially, the heat transfer rate is 60W when the temperature difference us becoming less the heat transfer gets reduced and going equilibrium at around 10W. Around 8250 seconds into the process, there is a notable shift in the behavior of the system. This is indicated by the convergence of the domain. In other words, the system reaches a state of equilibrium where the rate of heat transfer stabilizes. This convergence signifies that the system has reached a point where the temperature gradient between the Brass and the Helium has lessened, and the heat transfer rate has become relatively constant

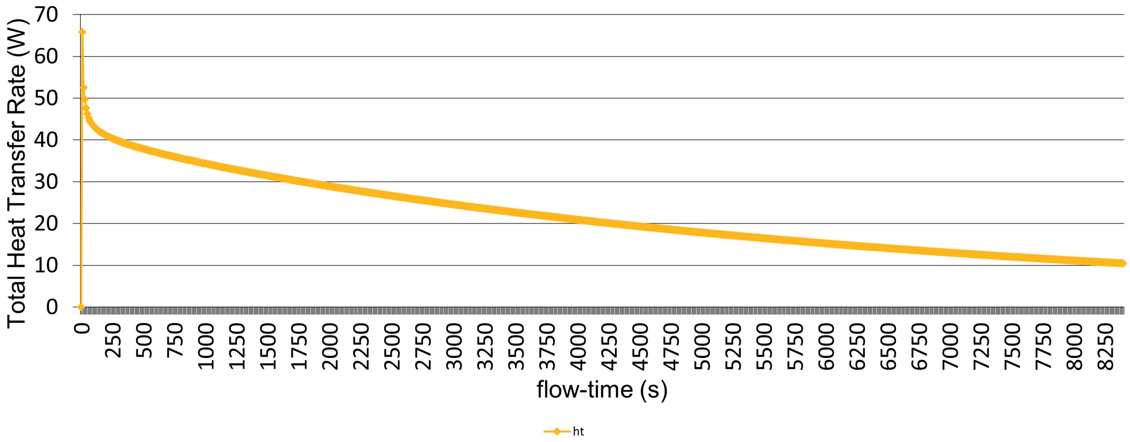

Figure 2: Variation of heat transfer rate with time

7.2 Temperature

The trend observed in the total heat transfer rate is mirrored in the temperature variation throughout the domain. At the beginning of the simulation, the Brass source is at a high temperature. Initially, there is a significant temperature gradient between the Brass and the Helium, driving heat transfer from the Brass to the Helium. This results in a rapid decrease in temperature of the Brass and an increase in temperature of the Helium as they seek equilibrium. Figure 3 illustrates this process. Initially, the temperature of the Brass decreases rapidly while the temperature of the Helium increases. This is indicative of the heat transfer occurring between the two materials. However, as time progresses, the temperature gradient between the Brass and the Helium diminishes as they approach thermal equilibrium. Around the 8250-second mark, the temperature throughout the domain begins to stabilize. This stabilization suggests that the system has reached a state where the temperature gradient has minimized, and the temperature distribution within the domain has become relatively constant.

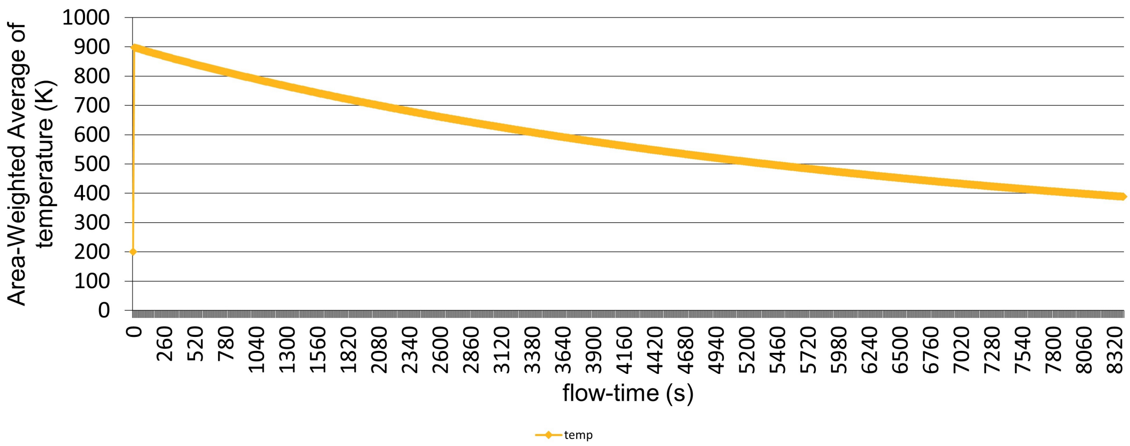

Figure 3: Variation of temperature with time

Figure 4 shows the static temperature variation around the brass.

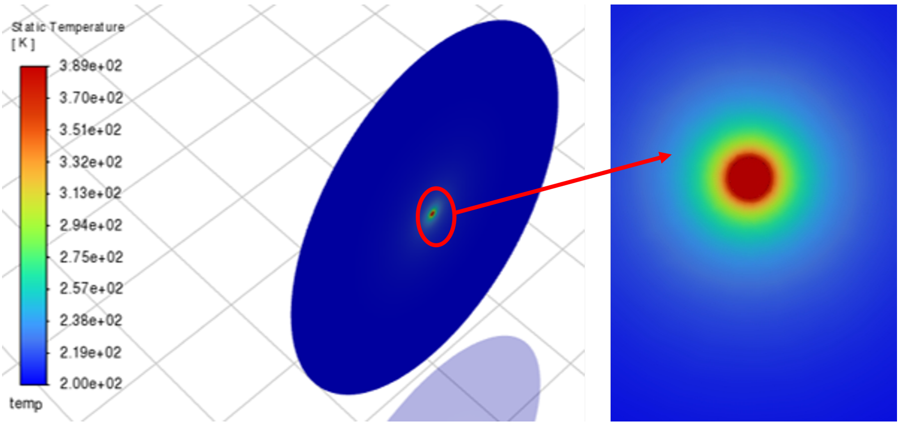

Figure 4: Static temperature

7.3 Surface heat transfer coefficient

The surface heat transfer coefficient, often denoted by h, is a crucial parameter in heat transfer analysis, particularly when considering convective heat transfer between a solid surface and a fluid (liquid or gas). It represents the rate of heat transfer per unit area per unit temperature difference between the surface and the fluid. Here the maximum and minimum Surface heat transfer coefficient recorded near the interface is $\pm 9.69 W/m^2K$

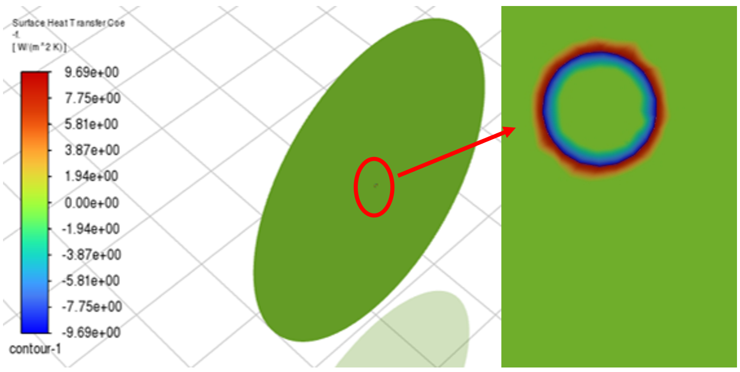

Figure 5: Surface heat transfer coefficient

7.4 Total surface heat flux

The total surface heat flux, denoted as Q_s represents the total amount of heat transferred per unit time through a surface. It is a combination of the heat transfer due to conduction, convection, and radiation. Since in the current work only conduction is focused rest effects are off its the indicated contour only accounts for surface heat flux by conduction only shown in figure 6. Here the maximum and minimum Surface heat transfer coefficient recorded near the interface is $972 W/m^2$.

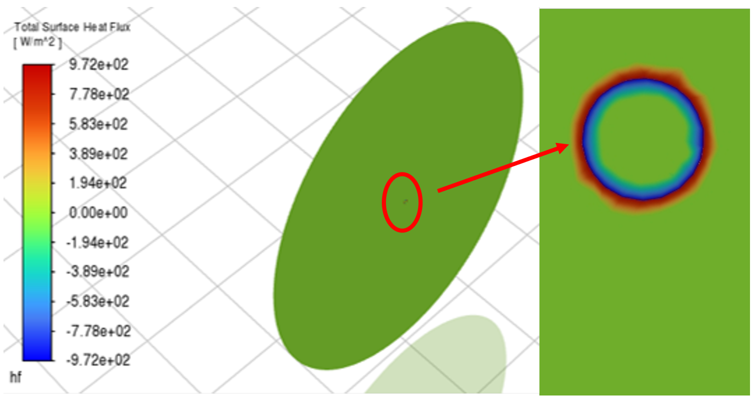

Figure 6: Total surface heat flux

8 Conclusion

In the current project, we've delved into a detailed examination of temperature dynamics and heat transfer rates between brass and helium, leveraging the capabilities of the commercial software Ansys Fluent. This investigation has allowed us to gain significant insights into the thermal behavior of the system. Our findings reveal a crucial moment of thermal equilibrium between brass and helium, occurring approximately at 8252 seconds into the simulation. This point marks a state where the temperatures of brass and helium stabilize, indicating a balance in the heat exchange between the two materials. Understanding this equilibrium is vital for various applications. For instance, in systems where brass components are in contact with helium coolant, such as in certain types of cooling systems or heat exchangers, knowing the exact timing of thermal equilibrium can optimize efficiency and performance.

Acknowledgments

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References

[1] ANSYS Fluent et al. Ansys fluent theory guide. *Ansys Inc., USA*, 15317:724–746, 2011.

[2] Frank P Incropera, David P DeWitt, Theodore L Bergman, Adrienne S Lavine, et al. *Fundamentals of heat and mass transfer*, volume 6. Wiley New York, 1996.

[3] John E Matsson. *An Introduction to Ansys Fluent 2023*. Sdc Publications, 2023.