Computational Fluid Dynamic Analysis of Scram Jet Combustion Chamber

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Abstract- *Heat Transfer is the science that predicts the energy transfer across the materials as result of the temperature difference. It is well known that there are three fundamental modes of heat transfer namely Conduction, Convection and Radiation.*

It has become exceedingly important for an engineer to possess a clear understanding of the principles of heat transfer and its applications to a large number of problems. Engineers are constantly confronted with the need to maximize or minimize the heat transfer rates and to maintain the integrity of materials under conditions of extreme temperatures. In order to determine the temperature distribution across the walls of combustion chambers and nozzles that possess hot gases, heat transfer coefficient is an important parameter to be evaluated in heat transfer analysis as the heat transfer in the engine components takes place mainly by convection from the hot gases to the surrounding walls. It is necessary to combine equations of motion with those of heat conduction. Therefore the need for fluid flow analysis becomes evident while solving heat transfer problems, especially when the heat source is in the form of high temperature fluids as in the case of Propulsion systems.

In recent years there has been a vast increase in interest in supersonic combustion in connection with flight propulsion. In the typical propulsion unit, propellants enter the combustion chamber, gets ignited and escapes through the nozzle at very high speeds which are supersonic in nature. Because of these gases escaping through the nozzle the rocket receives momentum in the opposite direction according to Newton's Third Law of Motion.

I. DEFINITION OF HEAT

Heat is defined in physics as the transfer of thermal energy across a well-defined boundary around a thermodynamic system. The thermodynamic free energy is the amount of work that a thermodynamic system can perform. Enthalpy is a thermodynamic potential, designated by the letter "H", i.e., the sum of the internal energy of the system (U) plus the product of pressure (P) and volume (V). Joule is a unit to quantify energy, work, or the amount of heat.

Heat transfer is a process function (or path function), as opposed to functions of state; therefore, the amount of heat transferred in a thermodynamic process that changes the state of a system depends on how that process occurs, not only the net difference between the initial and final states of the process.

Thermodynamic and mechanical heat transfer is calculated with the heat transfer coefficient, the proportionality between the heat flux and the thermodynamic driving force for the flow of heat. Heat flux is a quantitative, vectorial representation of the heat flow through a surface.

In engineering contexts, the term heat is taken as synonymous to thermal energy. This usage has its origin in the historical interpretation of heat as a fluid (caloric) that can be transferred by various causes, and that is also common in the language of laymen and everyday life.

The transport equations for thermal energy (Fourier's law), mechanical momentum (Newton's law for fluids), and mass transfer (Fick's laws of diffusion) are similar, and analogies among these, three transport processes have been developed to facilitate prediction of conversion from any one to the others.

Thermal engineering concerns the generation, use, conversion, and exchange of heat transfer. As such, heat transfer is involved in almost every sector of the economy. Heat transfer is classified into various mechanisms, such as thermal conduction, thermal convection, thermal radiation, and transfer of energy by phase changes.

II. DEFINITION OF HEAT TRANSFER

Heat transfer is the exchange of thermal energy between physical systems. The rate of heat transfer is dependent on the temperatures of the systems and the properties of the intervening medium through which the heat is transferred. The three fundamental modes of heat transfer are conduction, convection and radiation. Heat transfer, the flow of energy in the form of heat, is a process by which a system changes its internal energy, hence is of vital use in applications of the First Law of Thermodynamics. Conduction is also known as diffusion, not to be confused with diffusion related to the mixing of constituents of a fluid.

The direction of heat transfer is from a region of high temperature to another region of lower temperature, and is governed by the Second Law of Thermodynamics. Heat transfer changes the internal energy of the systems from which and to which the energy is transferred. Heat transfer will occur in a direction that increases the entropy of the collection of systems.

Thermal equilibrium is reached when all involved bodies and the surroundings reach the same temperature. Thermal expansion is the tendency of matter to change in volume in response to a change in temperature.

III. HEAT TRANSFER MODES : CONDUCTION

Heat transfer processes are classified into three types. The first is conduction, which is defined as transfer of heat occurring through intervening matter without bulk motion of the matter. Figure 1.1 shows the process pictorially.

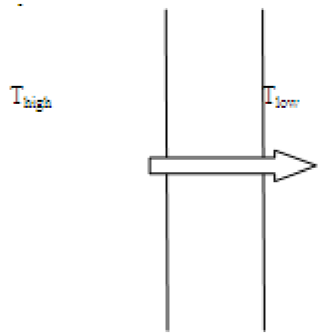


Figure 1.1 Conduction across a wall (Heat flows to right).

A solid (a block of metal, say) has one surface at a high temperature and one at a lower temperature. This type of heat conduction can occur, for example, through a turbine blade in a jet engine. The outside surface, which is exposed to gases from the combustor, is at a higher temperature than the inside surface, which has cooling air next to it. The level of the wall temperature is critical for a turbine blade. Conduction heat transfer the second heat transfer process is convection, or heat transfer due to a flowing fluid. The fluid can be a gas or a liquid; both have applications in aerospace technology. In convection heat transfer, the heat is moved through bulk transfer of a non-uniform temperature fluid. The third process is radiation or transmission of energy through space without the necessary presence of matter. Radiation is the only method for heat transfer in space. Radiation can be important even in situations in which there is an intervening medium; a familiar example is the heat transfer from a glowing piece of metal or from a fire.

Conduction rate equation is described by the Fourier Law: $q = -kA\nabla T$ r

Where: q = heat flow vector, (W)

k = thermal conductivity, a thermodynamic property of the material. (W/m K)

A = Cross sectional area in direction of heat flow. (m^2)

∇T = Gradient of temperature (K/m)

$= \partial T/\partial x\ i + \partial T/\partial y\ j + \partial T/\partial z\ k$

Note: Since this is a vector equation, it is often convenient to work with one component of the vector. For example, in the x direction: $q_x = -k\ A_x\ dT/dx$. In circular coordinates it may convenient to work in the radial direction: $q_r = -k\ A_r\ dT/dr$.

IV. HEAT TRANSFER MODES : CONVECTION

Convection is the transfer of thermal energy from one place to another by the movement of fluids. Although often discussed as a distinct method of heat transfer, convection describes the combined effects of conduction and fluid flow or mass exchange.

Two types of convective heat transfer may be distinguished:

1. Free or natural convection: when fluid motion is caused by buoyancy forces that result from the density variations due to variations of thermal temperature in the fluid. In the absence of an external source, when the fluid is in contact with a hot surface, its molecules separate and scatter, causing the fluid to be less dense. As a consequence, the fluid is displaced while the cooler fluid gets denser and the fluid sinks. Thus, the hotter volume transfers heat towards the cooler volume of that fluid. Familiar examples are the upward flow of air due to a fire or hot object and the circulation of water in a pot that is heated from below.

2. Forced convection: when a fluid is forced to flow over the surface by an external source such as fans, by stirring, and pumps, creating an artificially induced convection current.

Internal and external flow can also classify convection. Internal flow occurs when a fluid is enclosed by a solid boundary such when flowing through a pipe. An external flow occurs when a fluid extends indefinitely without encountering a solid surface. Both of these types of convection, either natural or forced, can be internal or external because they are independent of each other. The bulk temperature, or the average fluid temperature, is a convenient reference point for evaluating properties related to convective heat transfer, particularly in applications related to flow in pipes and ducts.

For a visual experience of natural convection, a glass filled with hot water and some red food dye may be placed inside a fish tank with cold, clear water. The convection currents of the red liquid may be seen to rise and fall in different regions, then eventually settle, illustrating the process as heat gradients are dissipated.

Convection-cooling is sometimes loosely assumed to be described by Newton's law of cooling.

Newton's law states that the rate of heat loss of a body is proportional to the difference in temperatures between the body and its surroundings while under the effects of a breeze. The constant of proportionality is the heat transfer coefficient. The law applies when the coefficient is independent, or relatively independent of the temperature difference between object and environment.

In classical natural convective heat transfer, the heat transfer coefficient is dependent on the temperature. However, Newton's law does approximate reality when the temperature changes are relatively small.

The basic relationship for heat transfer by convection is:

$$q = hA(T_a - T_b)$$

Where q is the heat transferred per unit time, A is the area of the object, h is the heat transfer coefficient, T_a is the object's surface temperature and T_b is the fluid temperature.

The convective heat transfer coefficient is dependent upon the physical properties of the fluid and the physical situation. Values of h have been measured and tabulated for commonly encountered fluids and flow of situations.

V. HEAT TRANSFER MODES: RADIATION

Thermal radiation occurs through a vacuum or any transparent medium (solid or fluid). It is the transfer of energy by means of photons in electromagnetic waves governed by the same laws. Earth's radiation balance depends on the incoming and the outgoing thermal radiation, Earth's energy budget. Anthropogenic perturbations in the climate system are responsible for a positive radiative forcing which reduces the net long wave radiation loss to space.

Thermal radiation is energy emitted by matter as electromagnetic waves, due to the pool of thermal energy in all matter with a temperature above absolute zero. Thermal radiation propagates without the presence of matter through the vacuum of space.

Thermal radiation is a direct result of the random movements of atoms and molecules in matter. Since these atoms and molecules are composed of charged particles (protons and electrons), their movement results in the emission of electromagnetic radiation, which carries energy away from the surface.

The Stefan-Boltzmann equation, which describes the rate of transfer of radiant energy, is as follows for an object in a vacuum:

$$Q = \epsilon \sigma T^4$$

For radiative transfer between two objects, the equation is as follows:

$$Q = \epsilon \sigma (T_a^4 - T_b^4)$$

Where Q is the heat flux, ε is the emissivity (unity for a black body), σ is the Stefan-Boltzmann constant, and T is the absolute temperature (in Kelvin or Rankine). Radiation is typically only important for very hot objects, or for objects with a large temperature difference.

Radiation from the sun, or solar radiation, can be harvested for heat and power. Unlike conductive and convective forms of heat transfer, thermal radiation can be concentrated in a small spot by using reflecting mirrors, which is exploited in concentrating solar power generation. For example, the sunlight reflected from mirrors heats thePS10 solar power tower and during the day it can heat water to 285 °C (545 °F).

VI. DIMENSIONLESS NUMBERS IN HEAT TRANSFER:

1.6.1 Reynolds Number

In fluid mechanics, the Reynolds number (Re) is a dimensionless quantity that is used to help predict similar flow patterns in different fluid flow situations. The concept was introduced by George Gabriel Stokes in 1851, but the Reynolds number is named after Osborne Reynolds (1842–1912), who popularized its use in 1883

The Reynolds number is defined as the ratio of inertial forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions.[5] Reynolds numbers frequently arise when performing scaling of fluid dynamics problems, and as such can be used to determine dynamic similitude between two different cases of fluid flow. They are also used to characterize different flow regimes within a similar fluid, such as laminar or turbulent flow:

a. laminar flow occurs at low Reynolds numbers, where viscous forces are dominant, and is characterized by smooth, constant fluid motion;

b. Turbulent flow occurs at high Reynolds numbers and is dominated by inertial forces, which tend to produce chaotic eddies, vortices and other flow instabilities.

In practice, matching the Reynolds number is not on its own sufficient to guarantee similitude. Fluid flow is generally chaotic, and very small changes to shape and surface roughness can result in very different flows. Nevertheless, Reynolds numbers are a very important guide and are widely used.

Reynolds number interpretation has been extended into the area of arbitrary complex systems as well: financial flows nonlinear networks, etc. In the latter case an artificial viscosity is reduced to nonlinear mechanism of energy distribution in network media. Reynolds number then represents a basic control parameter which expresses a balance between injected and dissipated energy flows for open boundary system. It has been shown that Reynolds critical regime separates two types of phase space motion: accelerator (attractor) and decelerator. High Reynolds number leads to a chaotic regime transition only in frame of attractor model.

The Reynolds number can be defined for several different situations where a fluid is in relative motion to a surface. These definitions generally include the fluid properties of density and viscosity, plus a velocity and a characteristic length or characteristic dimension. This dimension is a matter of convention – for example radius and diameter are equally valid to describe spheres or circles, but one is chosen by convention. For aircraft or ships, the length or width can be used. For flow in a pipe or a sphere moving in a fluid the internal diameter is generally used today. Other shapes such as rectangular pipes or non-spherical objects have an equivalent diameter defined. For fluids of variable density such as compressible gases or fluids of variable viscosity such as non-Newtonian fluids, special rules apply. The velocity may also be a matter of convention in some circumstances, notably stirred vessels. The Reynolds number is defined below for each case.

$$\mathrm{Re} = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{\rho \mathbf{v} L}{\mu} = \frac{\mathbf{v} L}{\nu}$$

Where:

V is the maximum velocity of the object relative to the fluid (SI units: m/s)

L is a characteristic linear dimension, (travelled length of the fluid; hydraulic diameter when dealing with river systems) (m) μ is the dynamic viscosity of the fluid (Pa·s or N·s/m^2 or kg/(m·s))

ν (nu) is the kinematic viscosity ($\nu = \mu/\rho$) (m^2/s)

ρ is the density of the fluid (kg/m^3).

Note that multiplying the Reynolds number by Lv/Lv yields $\rho v^2 L^2/\mu v L$, which is the ratio of the inertial forces to the viscous forces. It could also be considered the ratio of the total momentum transfer to the molecular momentum transfer.

1.6.2. Nusselt Number:

In heat transfer at a boundary (surface) within a fluid, the Nusselt number (Nu) is the ratio of convective to conductive heat transfer across (normal to) the boundary. In this context, convection includes both advection and diffusion. Named after Wilhelm Nusselt, it is a dimensionless number. The conductive component is measured under the same conditions as the heat convection but with a (hypothetically) stagnant (or motionless) fluid. A similar non-dimensional parameter is Biot Number, with the difference that the thermal conductivity is of the solid body and not the fluid.

A Nusselt number close to one, namely convection and conduction of similar magnitude, is characteristic of "slug flow" or laminar flow. A larger Nusselt number corresponds to more active convection, with turbulent flow typically in the 100–1000 range.

The convection and conduction heat flows are parallel to each other and to the surface normal of the boundary surface, and are all perpendicular to the mean fluid flow in the simple case.

$$\mathrm{Nu}_L = \frac{\text{Total heat transfer}}{\text{Conductive heat transfer}} = \frac{hL}{k}$$

where h is the convective heat transfer coefficient of the flow,

L is the characteristic length, k is the thermal conductivity of the fluid.

1.6.3. Prandtl Number:

The Prandtl number (Pr) or Prandtl group is a dimensionless number, named after the German physicist Ludwig Prandtl, defined as the ratio of momentum diffusivity to thermal diffusivity.[1] That is, the Prandtl number is given as:

$$\mathrm{Pr} = \frac{\nu}{\alpha} = \frac{\text{viscous diffusion rate}}{\text{thermal diffusion rate}} = \frac{\mu/\rho}{k/c_p\rho} = \frac{c_p\mu}{k}$$

where:

ν : momentum diffusivity (kinematic viscosity), $\nu = \mu/\rho$, (SI units: m^2/s)

α : thermal diffusivity, $\alpha = k/(\rho c_p)$, (SI units: m^2/s)

μ : dynamic viscosity, (SI units: Pa s = N s/m^2)

k : thermal conductivity, (SI units: W/m-K)

c_p : specific heat, (SI units: J/kg-K)

ρ : density, (SI units: kg/m^3).

Small values of the Prandtl number, Pr << 1, means the thermal diffusivity dominates. Whereas with large values, Pr >> 1, the momentum diffusivity dominates the behavior. For example, the listed value for liquid mercury indicates that the heat conduction is more significant compared to convection, so thermal diffusivity is dominant. However, for engine oil, convection is very effective in transferring energy from an area in comparison to pure conduction, so momentum diffusivity is dominant.

In heat transfer problems, the Prandtl number controls the relative thickness of the momentum and thermal boundary layers. When Pr is small, it means that the heat diffuses quickly compared to the velocity (momentum). This means that for liquid metals the thickness of the thermal boundary layer is much bigger than the velocity boundary layer.

The mass transfer analog of the Prandtl number is the Schmidt number.

1.6.4. Stanton Number

The Stanton number, St, is a dimensionless number that measures the ratio of heat transferred into a fluid to the thermal capacity of fluid. The Stanton number is named after Thomas Edward Stanton (1865–1931).[1] It is used to characterize heat transfer in forced convection flows.

$$St = \frac{h}{Gc_p} = \frac{h}{\rho u c_p}$$

where
h = convection heat transfer coefficient
ρ = density of the fluid
c_p = specific heat of the fluid
u = speed of the fluid

It can also be represented in terms of the fluid's Nusselt, Reynolds, and Prandtl numbers:

$$\mathrm{St} = \frac{\mathrm{Nu}}{\mathrm{Re}\,\mathrm{Pr}}$$

where
Nu is the Nusselt number;
Re is the Reynolds number;
Pr is the Prandtl number.

The Stanton number arises in the consideration of the geometric similarity of the momentum boundary layer and the thermal boundary layer, where it can be used to express a relationship between the shear force at the wall (due to viscous drag) and the total heat transfer at the wall (due to thermal diffusivity).

Aluminium diameter = 0.15m, length = 0.6m, and temperature of hot gases = 2222k

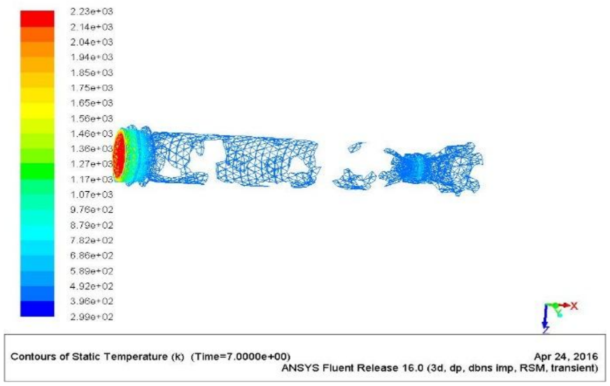


Fig 5.5: Contours of static Temperature (Time=7.6000e+01)

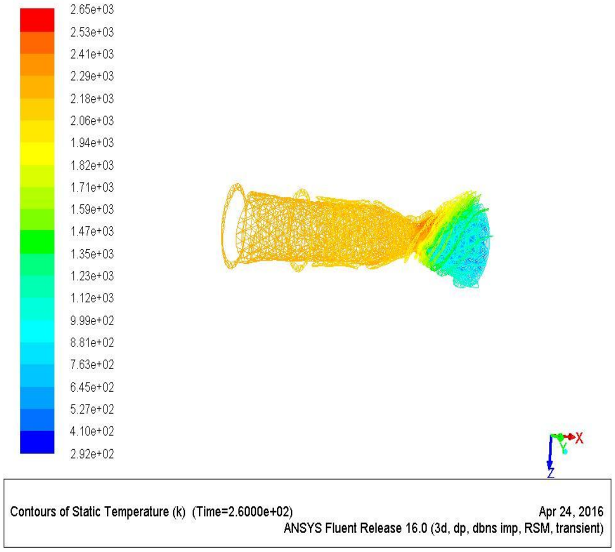
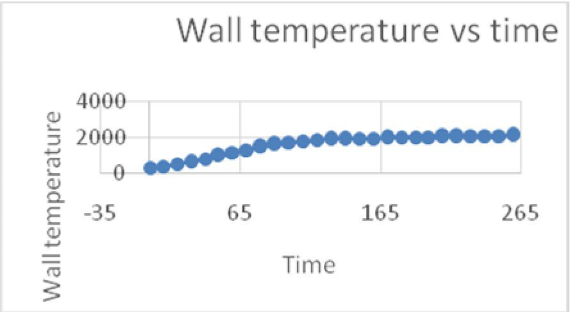
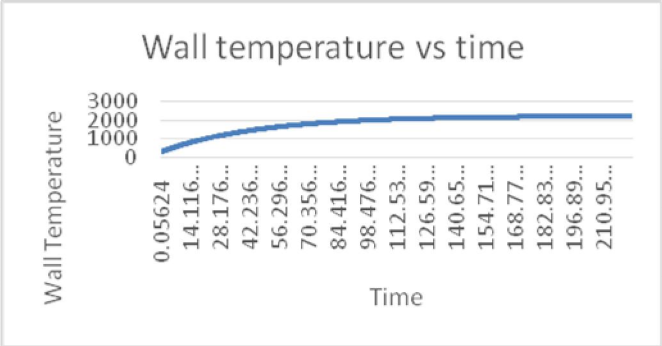


Fig 5.6: Contours of static temperature (Time=2.6000e+02)



Values obtained from CFD



Values obtained from schimidts method

Ti-6V-4Al diameter = 0.15m, length = 0.6m, and temperature of hot gases = 1200k

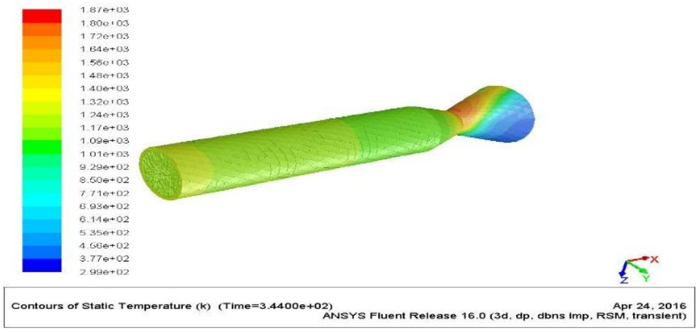


Fig 5.7: Contours of static Temperature (Time=3.4400e+02)

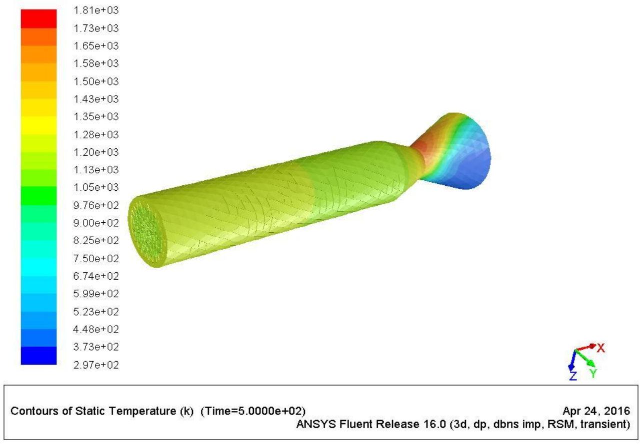


Fig 5.8: Contours of static temperature(Time=5.0000e+02)

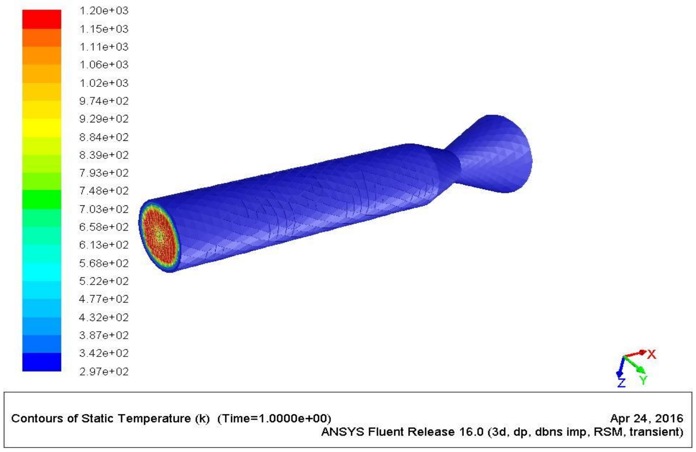
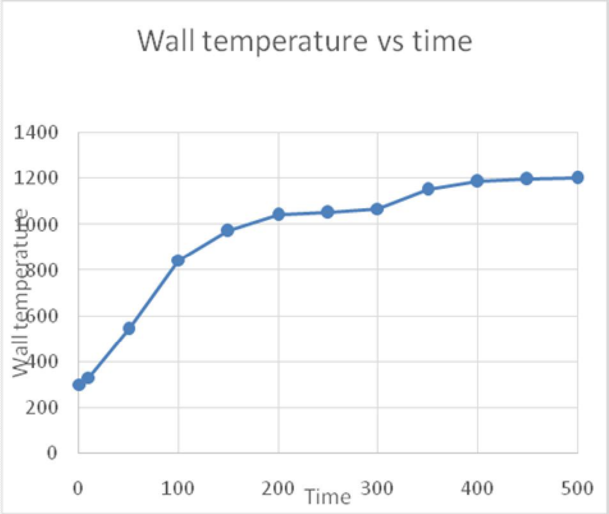
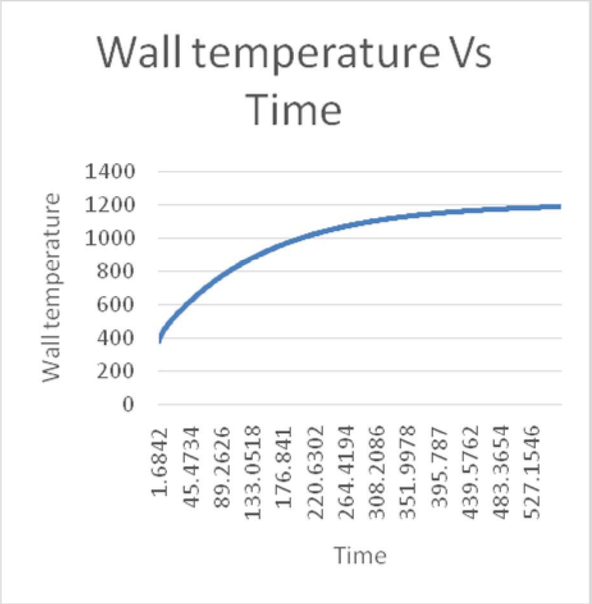


Fig 5.9: Contours of static temperature(Time=1.0000s+00)



Values obtained from CFD



Values obtained from schimidts method

Titanium diameter = 0.15m, length = 0.6m, and temperature of hot gases = 2222k

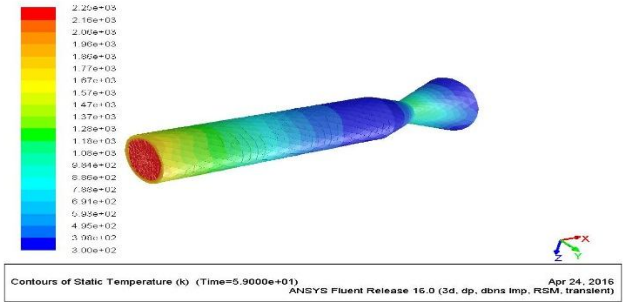


Fig 5.10: Contours of static temperature (Time=5.9000e+01)

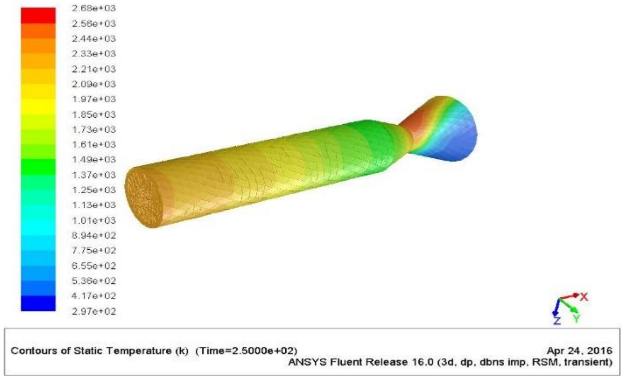
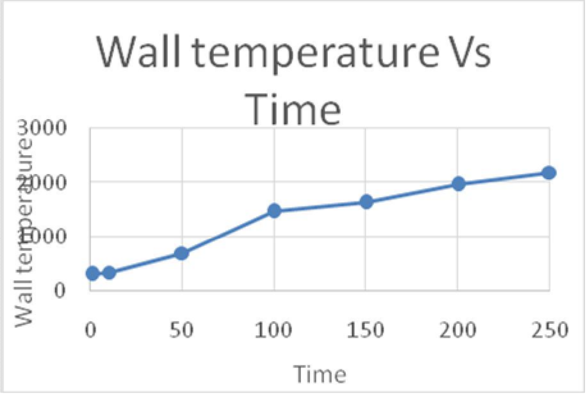
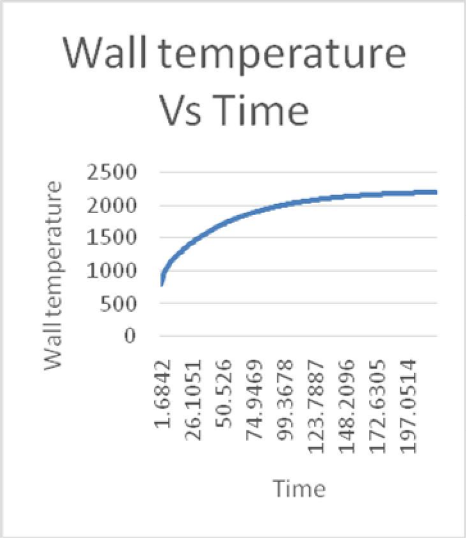


Fig 5.11: Contours of static temperature(Time=2.5000e+02)



Values obtained from CFD



Nimonic diameter = 0.15m, length = 0.6m, and temperature of hot gases = 1200k

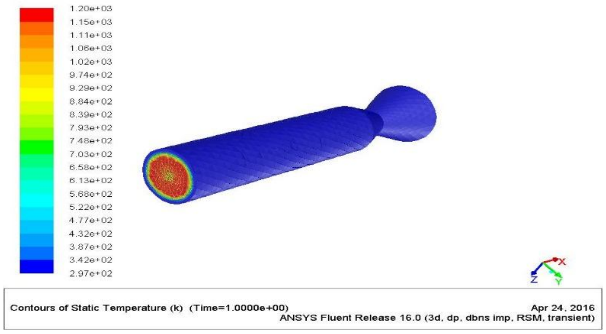


Fig 5.12: Contours of static Temperature(Time=1.0000e+00)

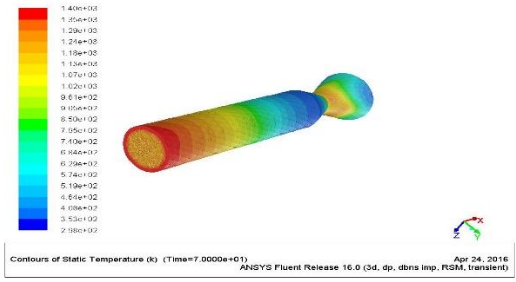


Fig 5.13:Contours of static Temperature(Time=7.0000e+01)

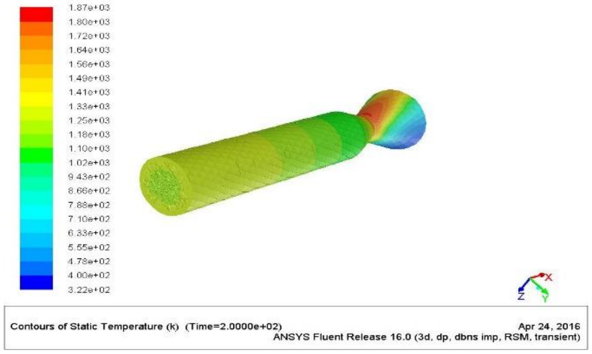
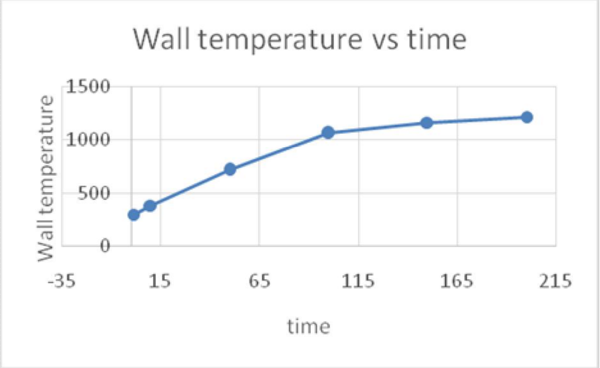
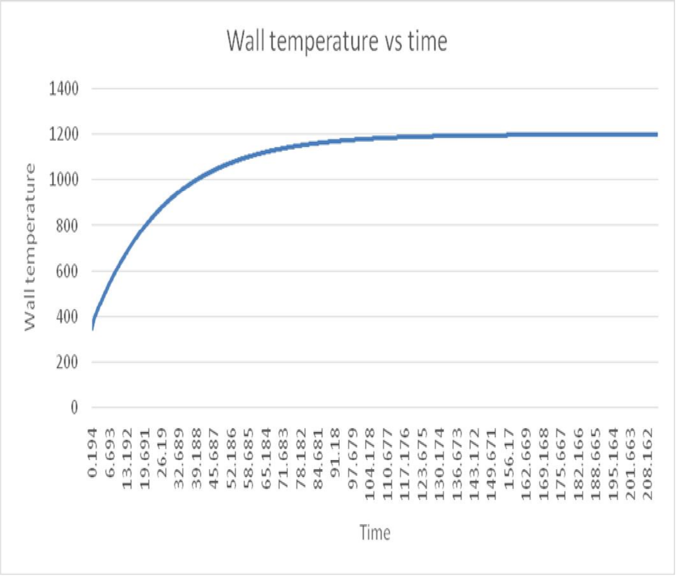


Fig 5.14: Contours of static temperature(time=2.0000e+02)



Values obtained from cfd



Values obtained from schimidts method

Nimonic diameter = 0.15m, length = 0.6m, and temperature of hot gases = 2222k

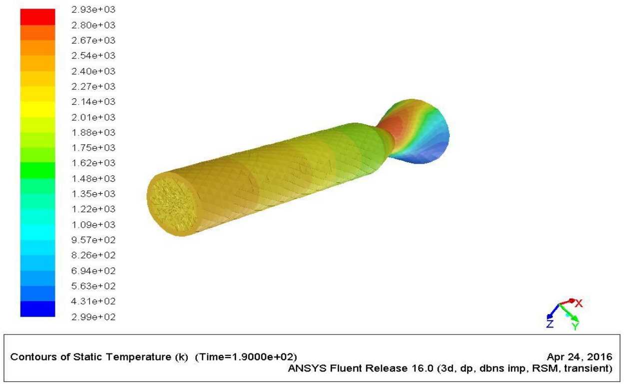
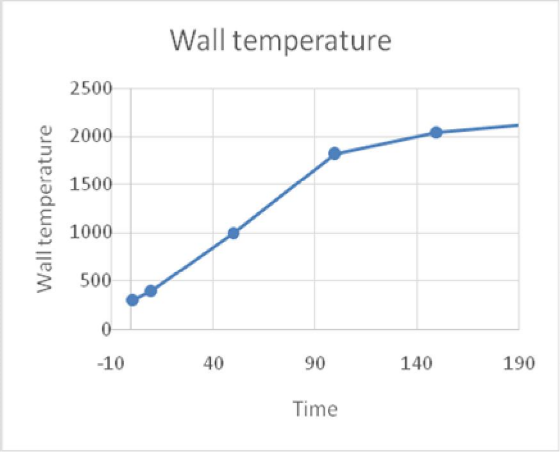


Fig 5.15: Contours of static temperature(time=1.5100e+02)



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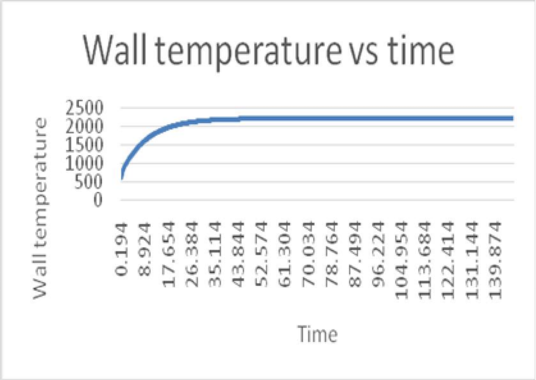
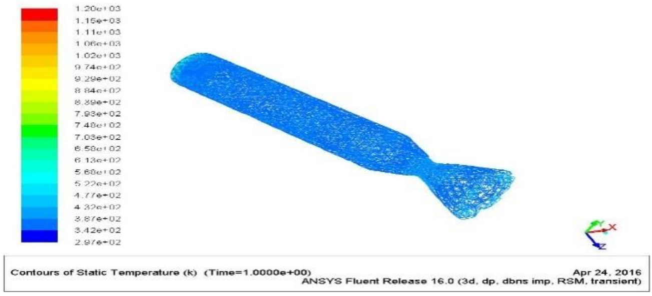


Values obtained from schimidts method



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S304 diameter = 0.15m, length = 0.6m, and temperature of hot gases = 1200k

Fig 5.17: Contours of static Temperature(Time=1.0000e+00)

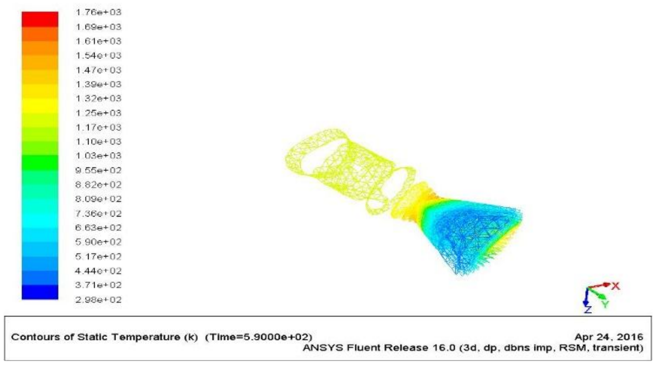
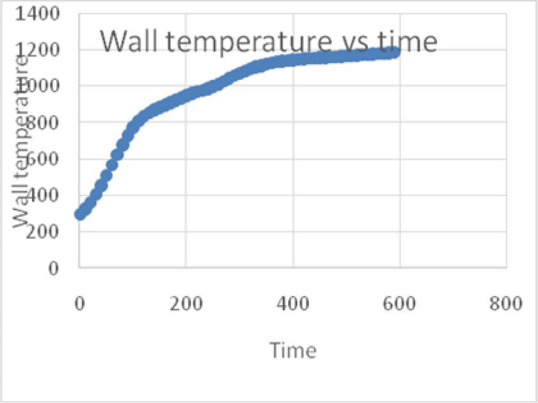


Fig 5.18: Contours of static temperature(time=5.9000e+02)



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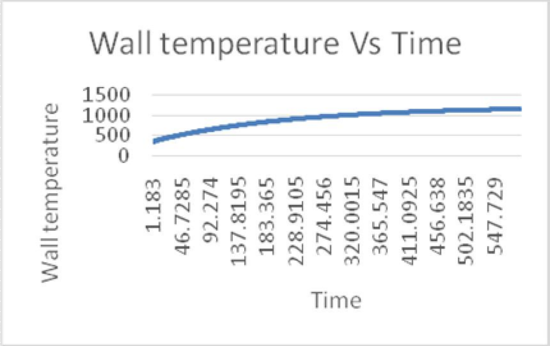


Values obtained from Schimidts method

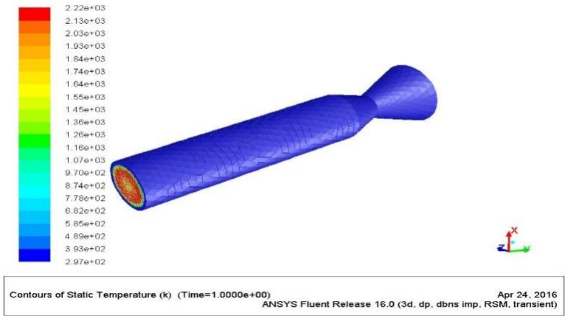


Fig 5.19: Contours of static temperature(Time=1.0000e+00)

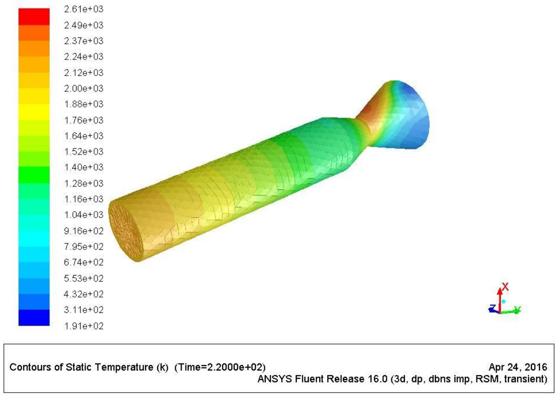
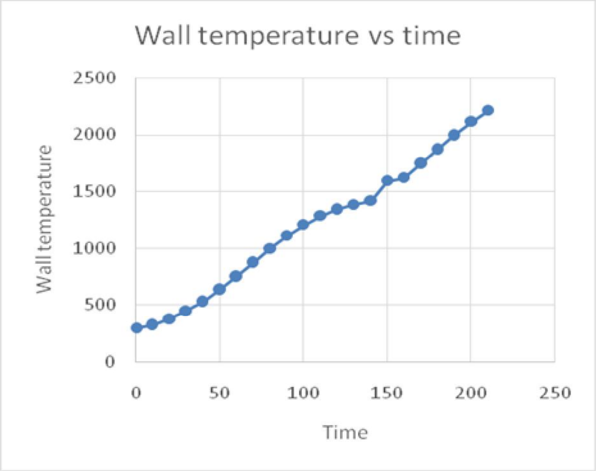
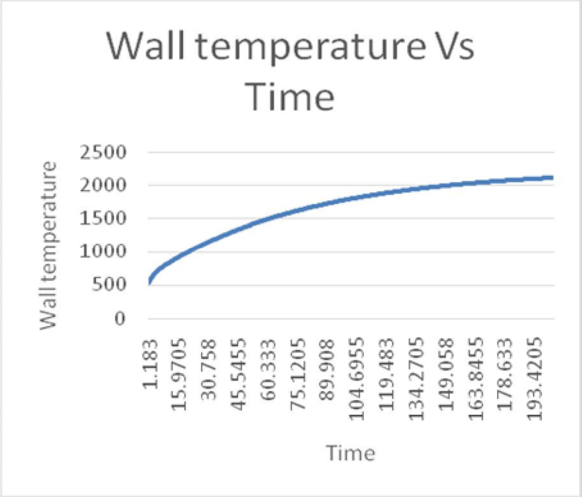


Fig 5.20: Contours of static temperature (time=2.2000e+02)



Values obtained from CFD



To attain the Allowable Temperature of Combustor materials when the maximum temperature inside the combustion chamber is 2500 K, for the considered dimensions and thickness of 0.015 m, time taken by the different materials are as follows

Material used	TIME (Seconds)	
	D = 0.1 m and L = 0.4 m	D = 0.2 m and L = 0.8 m
Aluminum 6061 Alloy	03	04
Titanium Alloy	06	08
SS – 304	27	30
Nimonic Alloy	52	38

Table 7.2

VII. CONCLUSION

1. Combustor made up of Nimonic alloy can withstand for longer test duration as Nimonic alloy is a super alloy capable of withstanding larger thermal stresses. It is suggested to make use of Nimonic alloy for longer combustor test duration based on the heat transfer analysis carried out.

2. Though Aluminum alloy has lower density resulting in lower component weight, it cannot be applicable for the combustor tests planned for the longer duration of time as the combustor attains its permissible temperature in less time.

VII. SCOPE OF FUTURE WORK

In order to increase the operating time of the combustion chamber, actively cooled system can be adapted. The Thermal Analysis of the Combustor walls can be carried out using various coolants and cooling passages accordingly. Alternatively, composite liners are also used for combustors as a back up to metallic casings for reasonable operating time.

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