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Numerical Investigation Of A Scram Jet Using DNS Method

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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.

The present work deals with the heat transfer analysis of the uncooled -combustion chamber. The study includes the temperature distributions across the thickness of the combustion chamber and estimation of the maximum time upto which the system can withstand the temperature under given operating conditions. A VB script code is developed to obtain the temperature distributions with respect to the time across the walls of the combustion chamber. Based on the heat transfer analysis, the maximum permissible test durations are estimated for the present uncooled combustion chamber of different materials with various configurations.. In order to increase the test duration, a cooling system is proposed for further studies.

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.

Correlations used:

Each flow geometry requires different correlations be used to obtain heat transfer coefficients. Initially, we will look at correlations for fluids flowing in conduits.

Most correlations will take the "Nusselt form":

$$\mathbf{Nu} = a\,\mathbf{Re}^{b}\,\mathbf{Pr}^{c}\,(\textbf{correction factors})$$

The correlations that follow are limited to conduit flow without phase change. Different geometries, boiling, and condensation will be covered in later lectures. Frictional heating (viscous dissipation) is not included in these correlations. This should not be a problem, since this phenomena is typically neglected except for highly viscous flows or gases at high mach numbers.

Unless otherwise specified, fluid properties should be evaluated at the "bulk average" temperature -- the arithmetic mean of the inlet and outlet temperatures:

$$T_b = \frac{T_{in} + T_{out}}{2}$$

Choosing a Correlation

When choosing a correlation, begin by asking:

1. What is the geometry? (Flow through a pipe, around an object, over a plane, etc.)
2. Is there a phase change?
3. What is the flow regime? (Check the Reynolds number to decide on laminar, transition, or turbulent flow.)
4. If the flow is laminar, is natural convection important? (The Grashof number will be used for this.)

Turbulent Conduit Flow -- No Phase Change

The historic equation for use in turbulent conduit flow is the Dittus-Boelter Correlation.

$$\mathbf{Nu} = 0.023\,\mathbf{Re}^{0.8}\,\mathbf{Pr}^{n} \quad n = 0.3 \text{ or } 0.4$$

The exponent on the Prandtl number depends on the service -- 0.4 is used for heating and 0.3 for cooling. Different values are needed because of the variation of viscosity with temperature.

Heating and cooling effect the velocity profile of a flowing fluid differently because of the temperature dependence of viscosity. Heating usually makes the fluid near the wall less viscous, so the flow profile becomes more "plug-like." Cooling has the opposite effect, increasing the viscosity near the wall and impeding heat transfer. The effect is most pronounced for viscous flows with large wall -- bulk temperature differences.

Instead of using different exponents for heating and cooling, a direct correction for viscosity can be used. This takes the form of the ratio of the viscosity at the bulk fluid temperature to the viscosity at the wall temperature. The ratio is then raised to the 0.14 power.

$$\phi_v = \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

When this is added, the result is the Seider-Tate Correlation (MSH Eq. 12.33), the correlation recommended for use in this class:

$$\mathbf{Nu} = 0.023\,\mathbf{Re}^{0.8}\,\mathbf{Pr}^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14}$$

Seider-Tate applies to "normal" fluids in turbulent flow in long, straight pipes, so:

$$0.7 < \mathrm{Pr} \le 160$$

$$\mathrm{Re} \ge 10{,}000$$

$$\frac{L}{d_i} \ge 60$$

Multiplicative correction factors are available to adjust for the entrance/exit consequences of short tubes:

$$\mathbf{Nu}_{corrected} = \mathbf{Nu}\left(1 + \left(\frac{d_i}{L}\right)^{0.7}\right)$$

and for pipe curvature

$$\mathbf{Nu}_{corrected} = \mathbf{Nu}\left(1 + 3.5\frac{d_i}{d_{coil}}\right)$$

If the conduit does not have a circular cross-section, the inside diameter should everywhere be replaced by the equivalent diameter

$$d_e = \frac{4S}{L_p}$$

Transitional Conduit Flow -- No Phase Change

Levenspiel (1998) recommends the following correlation for transition flow. The entrance effect correction may be omitted for "long" conduits.

$$\mathrm{Nu} = 0.116\left(\mathrm{Re}^{2/3} - 125\right)\mathrm{Pr}^{1/3}\left(1 + \left(\frac{d_i}{L}\right)^{2/3}\right)\left(\frac{\mu}{\mu_w}\right)^{0.14}$$

Laminar Conduit Flow -- No Phase Change

But many other works do not limit evaluation to cylindrical geometries, and use

$$\mathrm{Gz} = \frac{d_i}{L} \mathrm{Re\,Pr}$$

which differs from the MSH value by a factor of Pi/4. Consequently, you must be very careful to use the form that matches the correlation you are using. Those that follow are based on the standard form, NOT the MSH form.

Two correlations are provided for laminar flow, depending on the magnitude of the Graetz number. For Gz<100

$$\mathrm{Nu} = \left(3.66 + \frac{0.085\,\mathrm{Gz}}{1+0.047\,\mathrm{Gz}^{2/3}}\right)\left(\frac{\mu}{\mu_w}\right)^{0.14}$$

which approaches a limiting value of 3.66 in long pipes with uniform wall temperature (see MSH Fig, p. 344). For Gz>100, use

$$\mathrm{Nu} = 1.86\,\mathrm{Gz}^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14}$$

Both of these may need to be corrected when natural convection is significant.

Laminar Flow and Free Convection

Heat usually causes the density of a fluid to change. Less dense fluid tends to rise, while the more dense fluid falls. The result is circulation -- "natural" or "free" convection. This movement raises h values in slow moving fluids near surfaces, but is rarely significant in turbulent flow. Thus, it is necessary to check and compensate for free convection only in laminar flow problems.

The Grashof Number is used to assess the impact of natural convection

$$\mathrm{Gr} = \frac{d_i^{\,3} \rho_{film}^{\,2} g \beta (T_{wall} - T_{bulk})}{\mu_{film}^{\,2}}$$

It makes use of the coefficient of volume expansion:

$$\beta = \frac{1}{\hat{V}}\left(\frac{\partial \hat{V}}{\partial T}\right)_P$$

$$\approx \frac{1}{\hat{V}}\left(\frac{\Delta V}{\Delta T}\right) = \frac{2(\rho_1 - \rho_2)}{(T_2 - T_1)(\rho_1 + \rho_2)} \quad \text{most liquids}$$

$$\approx \frac{1}{\mathrm{T}} \quad \text{ideal gases}$$

The fluid properties used to calculate the Grashof number should be evaluated at the film temperature, the arithmetic mean between the bulk and wall temperatures. This will require determining an additional set of property values.

The Grashof Number provides a measure of the significance of natural convection. When the Grashof Number is greater than 1000, heat transfer coefficients should be corrected to reflect the increase due to free circulation. Multiplicative correction factors are available to apply to the Nusselt Number or the heat transfer coefficient (do NOT use both). These are:

$$\mathrm{Nu} = \mathrm{Nu}_{\mathrm{lam}}\left(0.87\left(1 + 0.15\,\mathrm{Gr}^{1/3}\right)\right)$$

or

$$h = h_{lam}\left(2.25\left(\frac{1 + 0.01\,\mathrm{Gr}^{1/3}}{\log_{10}\mathrm{Re}}\right)\right)$$

Aluminum 6061 Alloy

Composition:

It contains Aluminum with the traces of Chromium, Copper, Manganese, Iron, Silicon, Titanium and Zinc.

6061is an alloy containing magnesium and silicon as its major alloying elements. Originally called "Alloy 61S", it was developed in 1935. It has good mechanical properties and exhibits good weldability. It is one of the most common alloys of aluminum for general-purpose use.

It is commonly available in pre-tempered grades such as 6061-O (annealed), tempered grades such as 6061-T6 (solutionized and artificially aged) and 6061-T651 (solutionized, stress-relieved stretched and artificially aged).

Thermal Properties

i.Specific Heat– 908 J/Kg-K

ii. Thermal Conductivity – 200.98 W/m-K,

iii. Melting point – 933 K

iv. Maximum safe working temperature - 423 K

Applications

Commonly used in the manufacture of heavy-duty structures requiring good corrosion resistance, truck and marine components, railroad cars, furniture, tank fittings, general structural and high pressure applications, wire products, and in pipelines.

Temperature vs Tensile Strength :

Temperature (K)	Tensile Strength(MPa)
300	310
373	290
422	234
482	131

Table

Titanium Alloy

Composition: (by weight)

Titanium – 90%, Aluminium -6%, Vanadium – 4%, Fe – 0.25% (max).

Special characteristics

Ti6Al4V is the most widely used titanium alloy. It features good machinability and excellent mechanical properties. The Ti6Al4V alloy offers the best all-round performance for a variety of weight reduction applications in aerospace, automotive and marine equipment.

Ti6Al4V also has numerous applications in the medical industry. Biocompatibility of Ti6Al4V is excellent, especially when direct contact with tissue or bone is required.

Thermal Properties:

a. Specific Heat – 526 J/Kg-K

ii. Thermal Conductivity – 6.7 W/m-K

iii. Melting Point – 1873 K

iv. Maximum safe working temperature - 773 K

Applications

a. Direct Manufacturing of parts and prototypes for racing and aerospace industry.

b. Marine applications.

c. Chemical industry.

d. Gas turbines.

Temperature vs Tensile Strength :

Temperature (K)	Tensile Strength(MPa)
300	1000
373	950
573	830
773	580

Table

SS – 304

Composition: (by weight)

Carbon – 0.08% (max), Chromium – 20% (max), Nickel – 10.5% (max), Manganese – 2% (max), Silicon – 1% (max), traces of Nitrogen, Phosphorus, Sulphur and remaining Iron.

Austenitic Cr-Ni stainless steel. Better corrosion resistance than Type 302. High ductility, excellent drawing, forming, and spinning properties. Essentially non-magnetic, becomes slightly magnetic when cold worked. Low carbon content means less carbide precipitation in the heat-affected zone during welding and a lower susceptibility to intergranular corrosion

Thermal properties:

i Specific Heat 500 J/Kg-K (at 373 K),

ii. Thermal Conductivity 16.2 W/m-K(373 K),

21.5 W/m-K (at 773 K).

iii. Melting Point 1708 K

iv. Maximum safe working temperature - 1000 K

Applications

a .Kitchen benches, sinks, troughs, equipment and appliances

b .Architectural paneling, railings & trim

c. Chemical containers, including for transport

d. Heat Exchangers

Temperature vs Tensile Strength :

Temperature (K)	Tensile Strength(MPa)
300	800
500	720
750	580
1000	230

Table

Nimonic Alloy

Composition:

Chromium – 21% (max), Iron – 5% (max), Manganese – 1 % (max), Silicon -1% (max), Carbon – 0.15% (max) and remaining Nickel.

Features

Nimonic is a registered trademark of Special Metals Corporation that refers to a family of nickel-based high-temperature low creep superalloys. Nimonic alloys typically consist of more than 50% nickel and 20% chromium with additives such as titanium and aluminum. The main use is in gas turbine components and extremely high performance reciprocating internal combustion engines.

Thermal properties:

i.Specific Heat– 461 J/Kg-K

ii. Thermal Conductivity – 11.05 W/m-K,

iii. Melting point – 1926 K

iv. Maximum safe working temperature - 1123 K

Applications:

Due to its ability to withstand very high temperatures, Nimonic is ideal for use in aircraft parts and gas turbine components such as turbine blades and exhaust nozzles on jet engines, for instance, where the pressure and heat are extreme. It is available in different grades, including Nimonic 75, Nimonic 80A, and Nimonic 90.

Temperature vs Tensile Strength :

Temperature (K)	Tensile Strength(MPa)
300	1200
500	1060
750	850
1000	450

Table

II. HEAT TRANSFER ANALYSIS:

Heat Transfer Analysis of a Cooled Chamber:

Heat transfer in a cooled chamber can be described as the heat flow between two moving fluids through a multi-layered partition. The figure below shows schematically.

combustion chamber side coolant side

Gas side Heat Transfer

The primary step in the design of a thrust chamber cooling system analyzes heat transfer from the combustion gases to the chamber walls that occurs by forced convection. Before the gases transfer the heat to the wall, the heat energy must pass through a segment of stagnant gas layer along the wall. The basic correlation for this complicated convective heat transfer can be given by the equation,

$$q = h_g(T_{aw}- T_{wg})$$

where 'q' is the heat flux in KJ/m^2- s.

h_g is the gas side heat transfer coefficient in KJ/m^2s-K

T_{aw} is adiabatic wall temperature of the gas in K,

T_{wg} is the hot gas side local chamber wall temperature in K.

The adiabatic wall temperature of the combustion gas at a given location in the thrust chamber may be obtained from the following expression.

$T_{aw} = T_c[\{1+r((\gamma-1)/2)M^2\}/\{1+((\gamma-1)/2)M^2\}]$

T_c is nozzle stagnation temperature.

M is the Mach Number.

The relationship between the wall temperature and the heat flux, which depends on the heat transfer coefficient h_{gc} of the hot gas can be predicted with the sufficient accuracy for the turbulent heat transfer of the hot gases flowing in a constant area duct:

$Nu = 0.026(Re)^{0.8}(Pr)^{0.4}(L/d)^{0.055}$

Nu = Nusselt's Number = $h_{gc}d/ k$

Re = Reynold's Number =$\rho vd/\mu$

Pr = Prandtl Number = $\mu c_p/k$

μ= viscosity of the material at bulk temperature in kg/m-s,

d = chamber diameter in 'm',

k = coolant thermal conductivity in kJ/s-m-K,

ρ= density of the wall material in kg/m^3,

v = hot gas velocity in m/s,

c_p = material specific heat, kJ/kg-K

Coolant Side Heat Transfer:

The heat transfer can be calculated by using the relation

$Q_C = H (T_{aw} – T_0)$

H = Overall heat transfer coefficient W/ m^2-K,

T_{aw} = adiabatic wall temperature in K,

T_0 = Coolant side bulk temperature in K.

The bulk temperature of the most coolants should be kept below the critical temperature, since the vapor film heat transfer coefficient would be too low to cool the wall effectively. The cooling capacity of the liquid state regeneration system can be estimated by

$Q_C = W_CC_P(T_{CC} – T_{CI})$

Q_C = Coolant heat capacity kJ/s,

W_C = Coolant mass flow rate, kg/s,

C_P = coolant specific heat at constant pressure, kJ/kg-k,

T_{CC} = critical coolant temperature,k,

T_{CI} = Coolant inlet temperature

Uncooled Combustion Devices:

An uncooled metal thrust chamber is the simplest type. The uncooled walls essentially act as a heat sponge and absorb heat from the hot gases. Heat is transferred from the hot gases to the wall and from the wall to the surroundings. During the combustion process, the gas side of the wall is always hotter than the outside wall surface. Each local point within the wall experiences the higher temperature as the burning process proceeds.

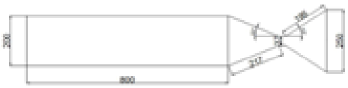
The heat transferred across the wall surface must be less than the heat absorbing capacity of the wall material below the critical temperature. If the heat transfer to the outside atmosphere is neglected, then this can be expressed in a simplified form

$Q\Delta t = -KA(dT/dL)\ \Delta t = WC_P\Delta t$

Q is the heat transferred in joules per second across an area of cross section in square meters. The heat conductivity depends on the material; dT/dL is the temperature gradient. W is the weight of the wall per unit area, Δt denotes the time increments in seconds. Detailed analysis of this problem requires iterative mathematical modeling.

Schmidt's Method :

A graphical or tabular method for solving complex heat transfer mathematical problems is credited to E.Schmidt. In this method a differential equation is replaced by a set of finite increments. This method is based on dividing the wall thickness into 'n' finite slabs of equal thickness. At any given time, the rate of heat conduction into a given slab exceeds the next slab by the amount of heat absorbed in raising the temperature of that particular slab.



$KA(T_{n-1}-T_n)/\Delta L - KA(T_n - T_{n+1})/\Delta L = A\,\Delta L\rho C_P(T_n'-T_n)/\Delta t$

Where T_n refers to the temperature of the slab under consideration, T_{n-1} to the slab ahead and T_{n+1} to the slab at lower temperature. T' refers to the temperature after a finite time Δt. If one designates the diffusivity α as $K/\rho C_p$, then the above equation can be written as

$(T_{n-1} + T_{n+1})/2 - T_n = (\Delta L)^2(T_n'-T_n)/2\alpha\,\Delta t$.

By proper choice of ΔL or Δt the quantity $2\alpha\,\Delta t/(\Delta L)^2$ can be made equal to one. Thus the equation becomes

$T_n' = (T_{n-1} + T_{n+1})/2$.

Thus the new temperature at the section 'n' is the arithmetic mean of temperatures previously prevailing at the sections ahead and behind at a time Δt prior to this event. This method is repeated for each slab and an approximate solution is found. It should be noted that this method in its simple form assumes uniform wall properties K, ρ and $C_p$which do not vary with temperature. This can be applied to flat plates, cylinders and cones such as thrust chambers and nozzles. The use flat plate relations are usually satisfactory, if the ratio of radius to wall thickness is greater than four.

III. ANALYSIS

Input Data given for the Analysis:

Typical propellant flow rate: 1000 g/s

Materials used are SS304, TITANIUM ALLOY, NIMONIC ALLOY and ALUMINIUM ALLOY

Figure All dimensions are in millimeters

Combustor Thickness = 15 mm

Stagnation temperature of fluid = 1500 &2500 K

Stagnation pressure = 5 bar

Nozzle exit pressure = 1 bar

IV. RESULTS AND CONCLUSIONS

The obtained results are as follows:

To attain the Allowable Temperature of Combustor materials, when the maximum temperature inside the combustion chamber is 1500 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	10	12
Titanium Alloy	36	45
SS – 304	129	149
Nimonic Alloy	220	252

Table

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	03	04

6061 Alloy		
Titanium Alloy	06	08
SS – 304	27	30
Nimonic Alloy	52	38

Table

V. 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.

CONCLUSION 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.

VI. 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.

