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Heat Transfer Analysis to Optimize The Water Cooling Scheme For Combustion Device

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ABSTRACT
Thermal Propulsion system is one kind of propulsion system which is used to drive torpedo. The present study focuses mainly on design of combustion device known to be thrust chamber or thrust cylinder. The chamber and nozzle wall and the injector face plate must be made of metals selected for high strength at elevated temperature coupled with good thermal conductivity, resistance to high temperature oxidation. chemical inertness on the coolant on the coolant side, and suitability for the fabrication method to be employed. In the case of certain monopropellants, the metal must not catalyze the decomposition. Although aluminum and copper alloys have been used successfully for combustion chambers and nozzles, stainless steels and carbon steels are in widest use today.A cooling jacket permits the circulation of a coolant, which, in the case of flight engines is usually one of the propellants. Water is the only coolant recommended. The cooling jacket consists of an inner and outer wall. The combustion chamber forms the inner wall and another concentric but larger cylinder provides the outer wall. The space between the walls serves as the coolant passage. The nozzle throat region usually has the highest heat transfer intensity and is, therefore, the most difficult to cool.
Key words: combustion device, thrust chamber.

I. INTRODUCTION

A solid torpedo engine employs solid propellants which are fed under pressure from tanks into a combustion chamber. The propellants usually consist of a grain and a solid fuel. In the combustion chamber the propellants chemically react (burn) to form hot gases which are then accelerated and ejected at high velocity through a nozzle, thereby imparting momentum to the engine. Momentum is the product of mass and velocity. The thrust force of a turbo motor is the reaction experienced by the motor structure due to the ejection of the high velocity matter.

The combustion chamber must be protected from the high rates of heat transferred to the chamber walls. There are at least 3 accepted ways of cooling the walls of a thrust chamber with liquid propellant: regenerative cooling, film cooling and transpiration or sweat cooling basic combustion chamber and the associated nomenclature that will be used throughout this report.

This is the same phenomenon which pushes a garden hose backward as water squirts from the nozzle or makes a gun recoil when fired. A typical turbo motor consists of the combustion chamber, the nozzle, and the injector. The combustion chamber is where the burning of propellants takes place at high pressure.

II. COMBUSTION CHAMBER

A combustion chamber is essentially a special combustion device where liquid propellants are metered, injected, atomized, mixed, and burned at a high combustion pressure to form gaseous reaction products, which in turn are accelerated and ejected at high velocities. Due to the high rate of energy given off, the cooling, stability of combustion, ignition, and injection problems deserve special consideration. Since combustion chambers are airborne devices, the weight has to be a minimum. A desirable combustion chamber therefore, combines lightweight construction with high performance, simplicity and reliability.

III. PROPERTIES OF INCONEL-718 MATERIAL

Inconel 718 is a precipitation-hardenable nickel-chromium alloy containing significant amounts of iron, niobium, and molybdenum along with lesser amounts of aluminum and titanium. It combines corrosion resistance and high strength with outstanding weldability, including resistance to postweld cracking. The alloy has excellent creep-rupture strength at temperatures up to 700 oC (1300 oF). Used in gas turbines, rocket motors, spacecraft, nuclear reactors, pumps, and tooling.

Typical Analysis in Percent:

Physical Properties:

Ni(+Co)	: 50 – 55	Cr : 17 – 21
Fe: bal Co	: 1	Mo : 2.8 - 3.3

Nb(+Ta)	: 4.75 - 5.5	Ti	: .65 - 1.15
Al	:0 .2 -.8	C	: 0.08
Mn	:0.35	Si	:0.35
B	:0.006	Cu	:0.3

Density: 8.19 g/cm3
Melting Point/Range: 1260 - 1336 oC (2300 - 2437 oF) J/kg · K Btu/lb · oF
Specific Heat: 435 0.104 µm/m · K µin./in. · oF
Average Coefficient of Thermal Expansion: 13.0 7.2 W/m · K Btu · in./ft2 · h · oF
Thermal Conductivity: 11.4 79
Electrical Resistivity: 1250 n · m
Curie temperature: -112 oC (-170 oF)
Typical Mechanical Properties:
At Room Temperature:
Ultimate Tensile Yield Strength Elongation in Elastic Modulus
Strength (0.2 % offset) 50 mm (2") (Tension) MPa ksi MPa ksi % GPa 106 psi
1240 180 1036 150 12 211 30.6
Hardness: 36 HRC

IV. DESIGN OF THRUST CHAMBER WALLS WITH STEADY- STATE HEAT TRANSFER

The largest part of the heat transferred from the hot chamber gases to the chamber walls is by convection. The amount of heat transferred by conduction is small and the amount transferred by radiation is usually less than 25% of the total. The chamber walls have to be kept at a temperature such that the wall material strength is adequate to prevent failure. Material failure is usually caused by either raising the wall temperature on the gas side so as to weaken, melt, or damage the wall material or by raising the wall temperature on the liquid coolant side so as to vaporize the liquid next to the wall.

The consequent failure is caused because of the sharp temperature rise in the wall caused by excessive heat transfer to the boiling coolant. In water-cooled chambers the transferred heat is absorbed by the water. The water must have an adequate heat capacity to prevent boiling of the water at any point in the cooling jacket.

V. PROBLEM DEFINITION

There are two types of torpedo propulsion systems namely electrical and thermal propulsion system. Naval Science and Technology Laboratory thermal propulsion division is in the process of developing thermal propulsion system. There are three major cycles for a torpedo thermal propulsion system namely open cycle semi closed cycle and closed cycle.

In an open cycle system the fuel and the oxidizer are burnt in a combustion chamber and the products of combustion are expanded in a turbine and directly routed out into the sea. The power output of this turbine is used to propel the torpedo forward.

A semi closed cycle system is an extension of an open cycle system. After the products have been expanded in a turbine, they are initially injected with sea water at the turbine outlet to reduce the temperature of the gas to the saturation temperature of steam at that pressure. This steam and gas mixture is passed through a hull-mounted of condenser of a torpedo, so that steam will be condensed in the condenser. Now this condensate and gas mixture is passed into a screw compressor and is compressed to slightly higher than the prevailing hydraulic pressure that of the sea.

In a closed cycle system the system as a whole differs from that of the other two systems. The main components of the closed cycle system are boiler reactor, turbine condenser and a pump. The boiler reactor contains a fixed amount of lithium metal. When an oxidizer like SF_6 is injected into the metal chamber and lot of heat is liberated..

VI. HEAT TRANSFER DISTRIBUTION

Heat is transmitted to all internal hardware surfaces exposed to hot gases, namely the injector face, the chamber and nozzles walls. The heat transfer rate or heat transfer intensity that is, local wall temperature and heat transfer per unit wall area, varies within the torpedo. The amount of heat transferred by conduction from the chamber gas to the walls in a torpedo thrust chamber is negligible. By far the largest part of the heat is transferred by means convection.

For constant chamber pressure, the chamber wall surface increases less rapidly than the volume as the thrust level is raised. Thus the cooling of chambers is generally easier in large thrust sizes, and the capacity of the wall material or the coolant to absorb all the heat rejected by the hot gas is generally more critical in smaller sizes, because of the volume-surface relationship.

Higher chamber pressure leads to higher vehicle performance, but also to higher engine inert mass. However, the resulting increase of heat transfer with chamber pressure often imposes design or material limits on the maximum practical chamber pressure for both liquid and solid propellant torpedoes. The high values are for the nozzle throat region of large bipropellant thrust chambers and high pressure solid torpedo motors. The lower are for gas generators, nozzle exit sections or small thrust chambers at low chamber pressures.

VII. PROCEDURE FOR CALCULATION

Velocity on Gas side (V_g) = $\frac{M_g}{(\rho_g \times A_g)}$

Where,
M_g = Mass of gas in Kg/sec
ρ_g = Density of gas in Kg/m^3
The heat flux from the hot gas to the wall becomes;
Heat flux (q) = $\dfrac{((T_{wg} - T_{wl}) \times 2\pi \times K_w}{\log_e\left(\dfrac{r_2}{r_1}\right)}$

Where,
T_{wg} = Wall side gas temperature in º K
T_{wl} = Wall side liquid temperature in º K
K_w = Thermal conductivity of wall in w/mk

Film mean temperature (T_f) = $\dfrac{T_g + T_{wg}}{2}$

Where,
T_g = Gas side temperature in º K
Viscosity of gas (μ_g) =
$$1.787 \times 46.6 \times 10^{-10} \times (M)^{-0.5} \times (T)^{0.6}$$
Where, M = Molecular weight

For a combustion gas mixture, the viscosity is linearly proportional to the first power of the temperature. Less is known about the effect of temperature on thermal conductivity, but the Eucken relation, which is based on the theory of heat conduction, indicates that the prandtl number should be nearly independent of T

Prandtl Number on gas side (Pr_g) = $\dfrac{4\gamma}{9\gamma - 1}$

Thermal conductivity on gas side
$$(K_g) = \frac{(\mu_g \times C_{pg})}{(\Pr_g)}$$
Where,
μ_g = Viscosity of gas in kg/m-Sec
Cp_g = Specific heat of gas in j/kg k

Reynolds Number on gas side
$$(Re_g) = \frac{(\rho_g \times V_g \times 2 \times r_1)}{(\mu_g)}$$
Where, V_g =Velocity on gas side in m/sec

In the chamber, strongly non-steady flow condition prevails, and so boundary layer in undoubtedly turbulent. It has been found that the heat transfer at the hot end of the chamber can be correlated by an equation of the Colburn type in which the pertinent length is the chamber diameter

Nusselt Number on gas side
$$(Nu_g) = 0.023(\text{Re}_g)^{0.8} \times (\Pr_g)^{0.33}$$
According to the Bartz, D.R. Theory Convective heat transfer coefficients as follows in gas and coolant side.

Heat transfer co efficient on gas side
$$(h_g) = \frac{(Nu_g \times K_g)}{(2 \times r_1)}$$
Where, Nu_g = Nusselt Number on gas side
K_g = Themal conductivity on gas side w/m-k

Velocity on Coolant side
$$(V_c) = \frac{Vw}{(A_d \times 600000)}$$
Where, V_w = Flow rate in LPM

Renolds number on Coolant side
$$(Re_c) = \frac{\rho_c \times V_c \times D_m}{\mu_c}$$
Where, ρ_c = Coolant side density in Kg/m^3
V_c = Coolant side Velocity in m/sec
D_m = Mean diameter in m

Prandtl Number on coolant side
$$(Pr_c) = \frac{\mu_c \times C_{pC}}{K_c}$$
Where, μ_c = Coolant side viscosity in kg/m-Sec
C_{pc} = Specific heat of coolant in j/kg k

Viscosity of coolant water
$$(\mu_{cw}) = 92125 \times Tw^{-3.3038}$$
Where, T_w = Wall temperature in º K

Stanton Number
$$(S_t) = 0.0278\,(\text{Re}_c)^{-0.2} \times (\Pr_c)^{-0.67} \times \left(\frac{\mu_c}{\mu_{cw}}\right)^{0.14}$$
Where
Re_c = Reynolds Number on coolant side
Pr_c = Prandtl Number on coolant side
μ_{cw} = Viscosity of coolant water in m^2/sec

Heat transfer coefficient on liquid side
$$(h_l) = St \times \rho_c \times V_c \times C_{pc}$$
Where, S_t = Stanton Number
V_c = Velocity on coolant side in m/sec
Cp_c = Specific heat of water in j/Kg-k

Overall heat transfer coefficient
$$(U) = \frac{1}{\left(\dfrac{r_2}{(r_1 \times h_g)}\right) + \left(\dfrac{r_2}{K_w}\right) \times \ln\left(\dfrac{r_2}{r_1}\right) + \left(\dfrac{1}{h_l}\right)}$$
Where,
r_1 = Inner radius of Chamber in m
r_2 = Outer radius of Chamber in m
h_g = Heat transfer coefficient on gas side in w/m^{2}k
h_l = Heat transfer coefficient on liquid side in w/m^{2}k
K_w = Thermal conductivity of chamber wall in w/m-k

Surface area (A_s)= $2\pi \times r_2 \times l$
Where, l = Length of Chamber in m

Log Mean Temperature Difference (LMTD) =
$$\frac{(D_{ti} - D_{te})}{\ln\left(\dfrac{D_{ti}}{D_{te}}\right)}$$
Heat transfer rate (Q)= $U \times A_s \times LMTD$

Where, U = Overall heat transfer coefficient in w/m^{2}k

Liquid temperature recalculated

$(Tl_r) = \frac{(Q \times 60000)}{(V_w \times \rho_c \times C_{pc})} + Tli$

Where, Q = Hear transfer rate in W
V_w = Flow rate of water in LPM
$T_{l\,i}$= Initial liquid temperature in ° K
C_{pc} = Specific heat of coolant in j/kg-K
Gas temperature recalculated (T_{gr}) =

$$Tg - \frac{(Q)}{(M_g \times C_{pg})}$$

Where, T_g=Gas temperature recalculated in ° K
M_g=Mass of gas in Kg/sec
C_{pc}=Specific heat of gas in j/Kg
$D_{tg} = (T_{ger} - T_{ge})$
$T_{ge} = (T_{ge} + D_{tg})$
$T_l = (T_l + D_{tw})$
Where, T_{ge}= initial Guess temperature in ° K
T_l= Liquid temperature in ° K

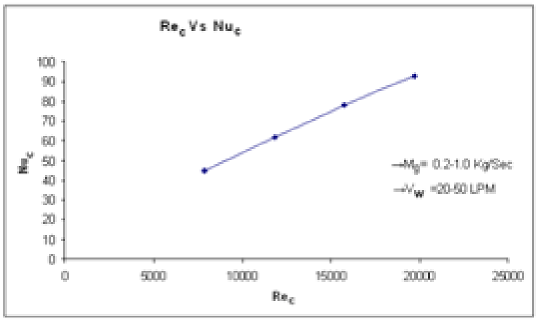

Fig.7.6.Variation of Re_c with Nu_c

This graph is plotted between the coolant side Reynolds number and coolant side Nusselt number. As the value of Reynolds number This graph is plotted between the coolant side Reynolds number and coolant side Nusselt number. on coolant side increases than Nusselt number on coolant side will be increases. These values taken at different mass of gas, and flow rates remain constant.

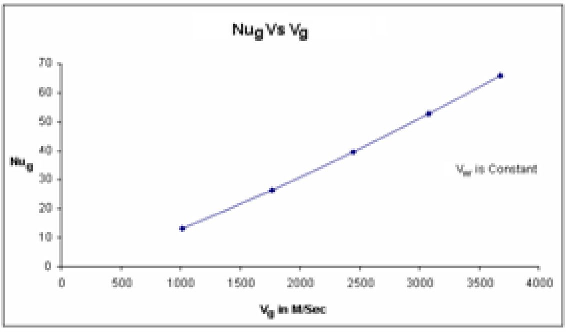

Fig.7.1. Variation of Nu_g with V_g

This graph is plotted between Nusselt number on gas side and Velocity on gas side, when Nusselt number on gas side increases then Velocity on gas side will be increases at different mass of gas raising order. Flow rate maintained at constant position

VIII. CONCLUSIONS

The following conclusions are arrived from the Steady-State heat transfer to the walls of Combustion Device.i.e Gas side and liquid side velocities are calculated,The steady state heat transfer coefficient of gas and liquid in a chamber have been estimated.The overall heat transfer coefficient, steady state gas and liquid side temperatures of the chamber wall are calculated at different mass of gas and water flow rate.The above calculated temperatures on the combustion chamber walls are developed by equations and validated by means of an iterative procedure.The software program in "C" was written to evaluate the temperatures and heat transfer coefficients pertain in to combustion chambers.

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