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Thermal design and analysis of cold plate with various proportions of ethyl glycol water solutions

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Abstract *:* In this paper, we present study on thermal design and analysis of cold plate with various proportions of Ethylene Glycol Water (EGW) solution for cooling high power dissipating Travelling wave Tube (TWT), which is used for high power applications in Electronic Warfare (EW) systems. The selection of right proportion of EGW with required volume flow rate is essential to cool the TWT when it is subjected to low temperature environment. This study predicts thermal performance of cold plate by theoretical and numerical approaches.

Key words : Cold plate, Ethylene Glycol Water solution, Liquid cooling.

INTRODUCTION

Military electronics equipment is deployed in low temperature environments and it should be operational at -10^{0}C. A Traveling-Wave Tube (TWT) is an electronic device used to amplify input Radio Frequency (RF) signals to high power in electronics systems. Higher heat transfer coefficients associated with liquids as compare to gases makes suitable for high heat flux applications [1]. As the electron beam focuses on small area of TWT called collector, produces more heat. The generated waste heat energy influences degradation in the performance of TWT in terms of gain and VSWR parameter.

Although, major portion of the input power is converted as RF output, the rest of the power input generates high heat flux and hence high temperature. Traditional conduction and air convection cooling mechanisms are not affordable in terms of size and weight penalties for high power density TWTs.

PROBLEM DESCRIPTION

The surface temperature of the TWT case shall be less than 90^{0}C for safe operation. Sixteen TWTs are mounted over the both sides of cold plate and glycol based water solution is passed through deep drilled channels to absorb the generated heat energy. As the cold plate system needs to be performing well in the stringent environmental conditions of -20^{0}C to +55^{0}C, the EGW solution is mixed to avoid the freezing of the coolant in the low temperature environmental conditions [2]. Various proportions like 25%, 30%, 40% and 50% ethylene glycol is added with water and the influence of Ethylene Glycol and water mixture on the TWT Temperature, pressure drop across the channels is estimated theoretically and is verified with the Computational Fluid Dynamics software by simulating the system.

Table 1: Ethylene glycol solution properties at 26.7^{0}C temperature

S. No	Property	Units	Ethylene glycol solution (% by volume)			
			25	30	40	50
	Dynamic viscosity	Centipoise	1.5	1.7	2.2	2.8
	Specific Heat	J/Kg K	3855.3	3777.4	3600	3411.6
	Thermal Conductivity	W/m K	0.521	0.511	0.468	0.433
	Freezing Point	^{0}C	-12	-16	-25	-37

DESIGN OF COLD PLATE

As the TWT has to work in harsh and rugged environment of 55^{0}C, coolant is supplied at 20^{0}C to the cold plate inlet by passing through external heat exchanger. The coolant properties at bulk mean temperature are provided at Table 1, which are used in the theoretical and numerical calculations. 6-pass flow channel with a diameter of 18mm and 3m length made in the cold plate to transfer the heat to the coolant.

The assumptions considered for finding out the maximum temperature are

a) Steady state conditions.
b) Specific heat of fluid is constant.
c) No leakage in the flow path.

As the TWTs are mounted on both sides of the cold plate, the resistances are conveniently evaluated by considering the half section of the cold plate.

A. Conductive Resistance

Two modes of heat transfer are involved in the design of cold plate. First, the heat is transferred from the TWTs to the cold plate through conduction and conductive resistance is calculated as.

$$R_{cond} = \frac{t}{kA_b} \quad (1)$$

where t is the thickness of the cold plate, k is the thermal conductivity of cold plate material and A_b is the cross sectional area normal to the heat flow.

B. Spreading Resistance

The variation in the cross sections of TWT foot print size of 90 x 30 mm dimension and the cold plate base size of 216 x 500 mm, spreading resistance presence involves in the heat path. The distance between the TWTs is assumed to be negligible and considered one side TWTs collective area as foot print area of heat source. Spreading resistance as per Seri Lee [3] is calculated by the relation as follows:

$$R_{sp} = \frac{\psi_{max}}{k\, r_1 \sqrt{\pi}} \quad (2)$$

where ψ_{max} is the constant and r_1 is the equalant radius of rectangular source.

C. Convective Resistance

The heat flows from the cold plate material (Al alloy 6061) to the EGW mixture in the convective mode of heat transfer. The cold plate performance is estimated for different flow rates of 6 LPM, 8 LPM, 10 LPM and 12 LPM through the channel. The temperature raise of the EGW solution is calculated as follows.

$$\Delta T_f = \frac{Q}{[\rho . C_p . A_C . V]} \quad (3)$$

where Q is total heat load, ρ is the density, C_p is the specific heat of the coolant, A_C is the cross sectional area of flow channel and V is the velocity of the flowing coolant.

In forced convection of heat transfer, the Reynolds number (Re) is given below

$$Re = \frac{V \rho D_h}{\mu} \quad (4)$$

where D_h is the hydraulic diameter of the channel and μ dynamic viscosity of the coolant.

For the internal flows, which is having Re>3000, Nusselt Number (Nu) is given by Dittus-Boelter equation [4]. The Prandtl Number (Pr) and other properties are evaluated at the bulk mean solution temperature.

$$Nu = 0.023\, Re^{0.8}\, Pr^{0.4} \quad (5)$$

As the cold plate channels are assumed as having smooth surface, friction factor for laminar flows,

$$f = \frac{Re}{64} \quad \text{for } Re < 2300 \quad (6)$$

$$f = (0.79 \ln Re - 1.64)^{-2} \quad \text{for } 10^4 < Re < 10^6 \quad (7)$$

where f is the frictional coefficient. The heat transfer coefficient (h) is critical parameter which predicts the amount of heat that will be transferred into the circulating EGW solution from the fluid boundary layer.

$$h = Nu \frac{k}{D_h} \quad (8)$$

The convective resistance which is a prominent component in the total resistance network analogy.

$$R_{conv} = \frac{1}{hA_s} \quad (9)$$

The total thermal resistance (R_t) from the TWT surface to the fluid temperature is as follows [5]

$$R_t = R_{cond} + R_{sp} + R_{conv} \quad (10)$$

The temperature raise of TWT surface ΔT_s is evaluated using following equation by considering the total heat dissipation (Q) of the TWTs.

$$\Delta T_s = Q \, x \, R_t \quad (11)$$

THERMAL ANALYSIS

The designed cold plate is modeled using solid works package and with gravity and steady state conditions are activated in the FloEFD package [6]. The overall computational domain selected was three dimensional, rectangular and created configurations as shown in Fig, 1.

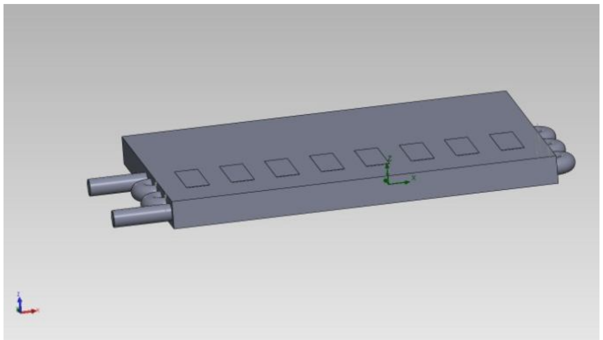

Fig 1: Isometric view of cold plate with heat sources

The focus of the study is the systematic variation of flow conditions and fluid properties. The effects of radiation and turbulence are quite relevant to simulate the model and considered in the present study. Aluminum alloy 6061 is selected for cold plate material. The computations were performed using commercial package FloEFD to approximate the governing equations.

The boundary conditions used in FloEFD were flow rate conditions and static pressure boundary at inlet and outlet respectively.

THEORETICAL RESULTS

Based on the design of cold plate, TWT temperature is calculated using resistance analogy. Fig. 2 shows the temperature variation of TWTs with respect to the flow rate for different proportions of EGW mixtures. For 6 LPM flow rate, EGW 25% had 3.4% better thermal performance over 30% EGW solution, 12.2% better performance over 40% EGW solution and 23.4% better performance over 50% EGW solution. The same trend in temperatures is following for other flow rates also. Fig. 3 shows the variation of pressure drop with flow rate.

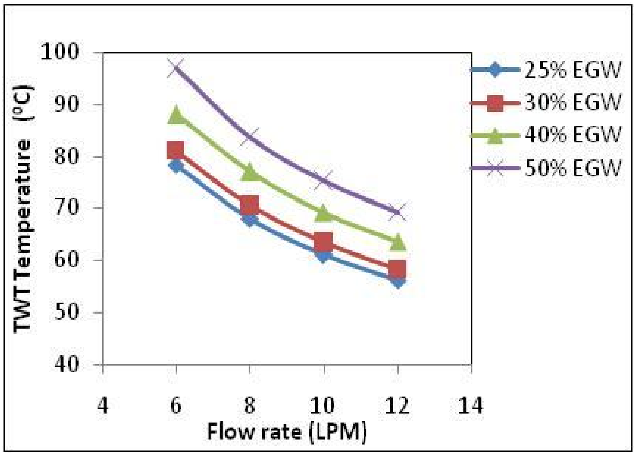

Fig 2: TWT temperature versus flow rate (Theoretical)

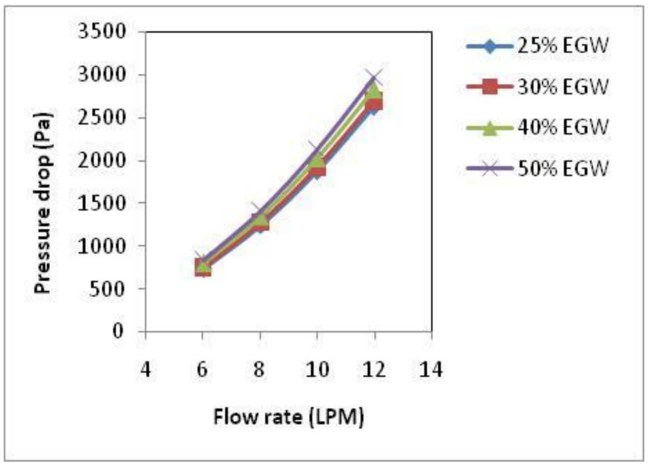

Fig 3: Pressure drop versus flow rate (Theoretical)

COMPUTATIONAL RESULTS

Considering the properties of the 25%, 30%, 40% and 50% ethylene glycol with water the TWT cooling system is simulated in CFD software. The case temperature of TWT is estimated for various proportions of fluid for a fixed mass flow rate through the cold plate.

Higher temperature value for 25% EGW solution with low flow rate of 6 LPM through cold plate can be seen in Fig. 4. Larger pressure drop value for 50% EGW solution with flow rate of 12 LPM through cold plate due to high velocities associated with more flow rate is shown in Fig. 5. Flow rates of 6 and 8 LPM with 40% and 50% EGW solutions are exceeding the limiting case temperature value of TWT is shown in Fig. 6. These flow rates not maintaining the TWTs in safe operating conditions. Higher heat flux and low specific heat offers maximum temperature for the low flow rate of 6 LPM for 50% EGW solution. The variations in temperature, when flow rates are 10 LPM and above are minimal. The pressure drop augments with increase of EG mixture due to the more dynamic viscosity is shown in Fig. 7. Cold plate thermal resistance variation with flow rate is shown in Fig. 8.

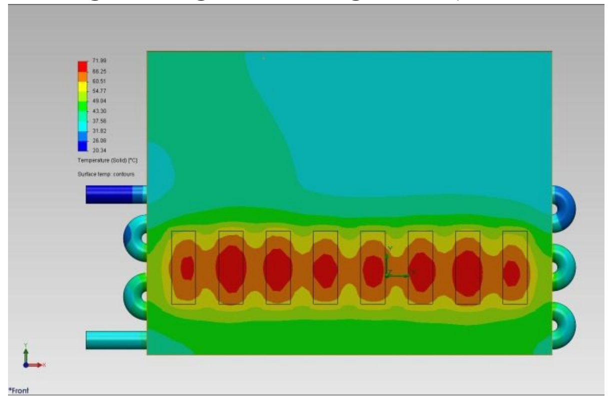

Fig 4: FloEFD temperature contours of 25% EGW with 6 LPM flow rate through cold plate.

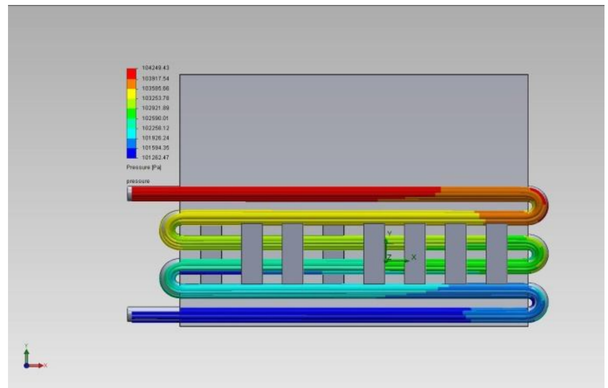

Fig 5: FloEFD pressure drop of 50% EGW with 12 LPM flow rate through cold plate.

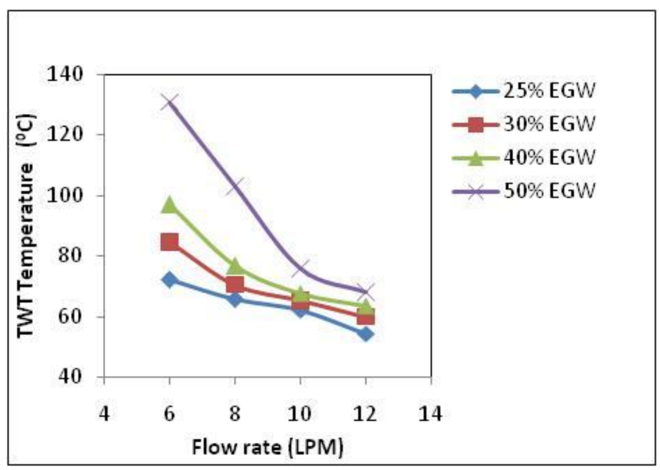

Fig 6: TWT temperature versus flow rate (Simulation)

Fig. 2 & 6 represents the theoretical & simulation values of TWT saturated surface temperature with respective to different EGW flow rates. The simulation results of 25%, 30% and 40% of EG proportions results are follows similar pattern of theoretical estimates. Whereas simulation results of 50% of EG proportion for the flow rate of 6 to 8 LPM observed high surface temperature due to voltile nature of the solution. However, 10-12 LPM follows same as theoretical pattern. Hence, it is suggested that high proportions of EG solution should maintain high flow rates for its safe operation.

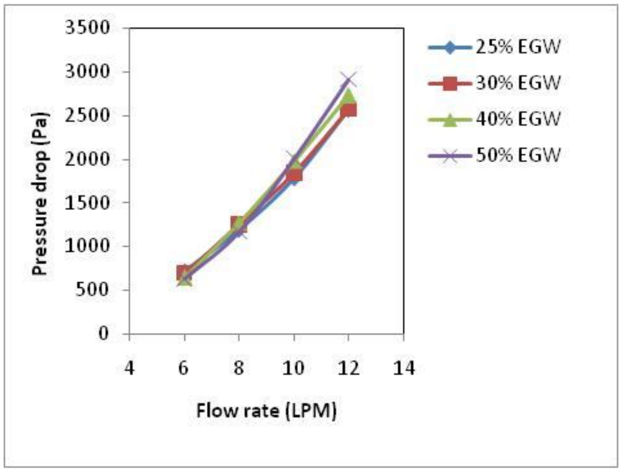

Fig 7: Pressure drop versus flow rate (Simulation)

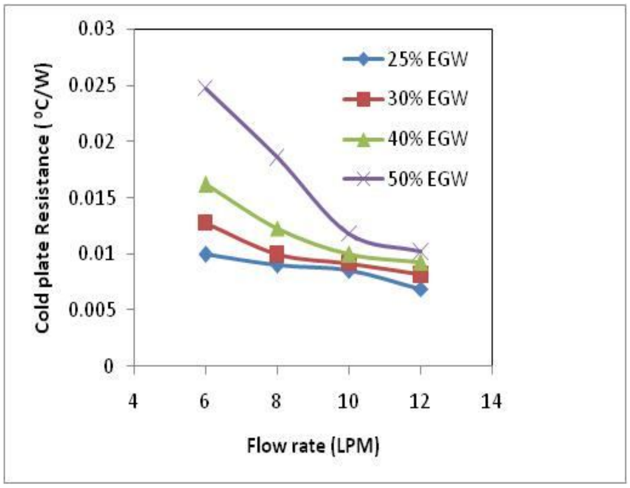

Fig 8: Cold plate Thermal resistance versus flow rate (Simulation)

CONCLUSION

Theoretical and computational investigations were performed to evaluate the thermal performance and pressure drop associated with deep drilled cold plate.

The temperature values are overshooting for increased addition of EG even though flow rate increases through the cold plate. Based on freezing conditions of stringent low temperature environment in which system to be operated, 30% EGW solution with 6 LPM flow rate are to be selected for safe and reliable performance of TWTs.

ABBREVIATIONS & ACRONYMS

A_b	Cross sectional area of cold plate base [m^2]
A_c	Cross sectional area of flow channel [m^2]
C_p	Specific heat of EGW solution [J/Kg K]
D_h	Hydraulic Diameter [m]
f	Friction Factor
h	Heat transfer coefficient [W/m^2 K]
k	Thermal conductivity of EGW solution [W/m K]
LPM	Liters Per Minute
N_u	Nusselt Number
Pr	Prandtl Number
Q	Total heat load [W]
R_e	Reynolds Number
R_{Cond}	Conductive Resistance [^{0}C/W]
R_{Conv}	Convective Resistance [^{0}C/W]
R_{sp}	Spreading Resistance [^{0}C/W]
R_t	Total Thermal Resistance [^{0}C/W]
t	Thickness of cold plate [m]
T_S	Surface Temperature of TWT case [^{0}C]
ΔT_S	Temperature raise of TWT [^{0}C]
v	velocity of EGW solution [m/s]

Greek symbols

μ	Fluid dynamic viscosity [Kg/m-s]
ρ	fluid density [Kg/m^3]

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[6] FloEFD 11.0.0 is a Computational Fluid dynamics product registered by Mentor Graphics, East Park, Shannon Co Clare, Ireland.