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Analytical Model of Cryo-Target in Thermo Vacuum Chamber

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***Abstract*— Nitrogen and Helium based Cryo-Target (CT) systems are used for various experimental, industrial and testing applications in high vacuum chambers. Thermal performance of CT systems depends upon a number of factors such as thermal exchange coefficient of coolant, various forms of heat losses, coolant properties, CT plate characteristics, externally applied heat loads etc. Therefore an analytical formulation is necessary in order to quantify the effect of such factors over thermal performance of CT system. In this paper analytical model is developed for flat plate CT system based on the positive root of heat balance quartic equation. Important analytical formulas related to characterization of thermal performance of CT systems are presented. This paper doesn't consider mixed phase flow in CT.**

***Index Terms* — Cryo- Target, Quartic equation, Single phase flow, Thermo-Vacuum Chamber**

I. INTRODUCTION

Cryo-Targets are small size thermal shrouds which are cooled under high vacuum with Helium or Nitrogen (liquid or gas). Their application ranges from space simulation tests of payloads [1], cold fingers [2], testing of components at low temperatures and various experiments at low temperature physics and cryogenics. One of the simplest designs of CT is a pair of plates separated by small distance to form a thermal shroud (as shown in Fig. 1) . Between these plates the coolant flows and low temperature on the plates are obtained. The testing objects then radiatively or conductively cooled by placing near to the cold plates. The temperature of the testing object can be varied by using control heaters. To avoid condensation and minimize impingement and radiative losses, CT system must be kept in high vacuum inside vacuum chamber and should be covered with Multi Layer Insulation (MLI).

For a number of reasons it is important to quantify the thermal behavior of CT plates with respect to the parameters that govern its temperature. For flat plate CT systems it is possible to develop an analytical formulation in the regime where conduction and convection heat transfer are linear with temperature .In formulating the problem we have assumed

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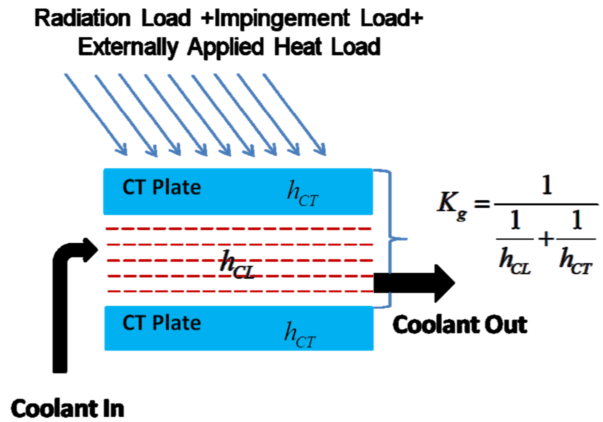

Fig. 1 Schematic diagram of flat plate CT system depicting coolant flow and various heat loads.

single phase flow of coolant inside CT. Also the 'global coefficient of thermal exchange (K_g)' between CT plate and coolant has been assumed to be a known quantity.

II. HEAT BALANCE EQUATION FOR CT PLATE

In steady state the total heat loads of CT is balanced by the heat absorbed by the coolant. Major heat loads on CT plate come from radiative losses, externally applied heat loads 'W', conduction losses and molecular bombardment (impingement). Balancing these heat loads with the heat absorbed by the coolant results in the following heat balance equation:

$$\varepsilon_g \sigma F A\,(T_c^4 - T^4) + f(R)\,(T_c - T) + CA\,p_c\sqrt{T_c} + W = K_g A\;(T - T_{CL}) \qquad (1)$$

In the above equation 'ε_g' is global emissivity [3], 'F' is view factor [4], 'A' is area of CT plate. 'T_c' and 'p_c' are the chamber temperature and pressure respectively. 'T_{CL}' and 'T' are coolant temperature and CT plate temperature respectively. The first term in LHS represents radiative heat loads. The second term represents the conduction losses due to finite thermal resistance 'R' of CT supporting arrangements. The conduction losses through CT supporting arrangements (which are usually glass fiber blocks or Teflon sheets) can be approximated as (T_c-T)/R where the temperature difference across CT supports are taken as (T_c-T). In this case f(R) =1/R. The third term in LHS represents the impingement power which come from molecular bombardment on CT plate. If thermal energy of the molecules are taken as E= (3/2)k.T_c then the coefficient 'C' is $C = \sqrt{9k/(8\pi m)}$ where 'm' is mass of molecule. 'W' represents the externally applied heat loads (if any). RHS of (1) represents the total heat absorbed by the coolant. K_g is global coefficient of thermal exchange between coolant and CT plate. It is given as $K_g=(h_{CL}^{-1}+h_{CT}^{-1})^{-1}$, where h_{CL} and h_{CT} are the convection and conduction coefficient of the coolant and CT plate respectively. Units of h_{CL} and h_{CT} are same $(W/m^2.K)$

Rearranging the terms in (1) gives the following quartic equation for CT temperature

$$T^4+\left(\frac{f(R)}{\varepsilon_g A\sigma F}+\frac{K_g}{\varepsilon_g\sigma F}\right)T-\left(T_c^4+\frac{Cp_cT_c^{1/2}}{\varepsilon_g\sigma F}+\frac{W}{\varepsilon_g A\sigma F}+\frac{f(R)\,T_c}{\varepsilon_g A\sigma F}+\frac{K_gT_{CL}}{\varepsilon_g\sigma F}\right)=0 \tag{2}$$

Equation 2 is the required heat balance quartic equation. It contains all the parameters that govern the performance CT temperature 'T'. Next we discuss the general analytical solution of (2).

III. ANALYTICAL SOLUTION OF HEAT BALANCE EQUATION

It can be noted that for most of the heat problems conduction and convection are linear in temperatures [5] while radiations are quartic in temperatures. Therefore a large class of radiative heat problems can be modeled through the following quartic type heat balance equation:

$$T^4+\alpha T-\beta=0 \tag{3}$$

where α >0, β>0. Comparing (3) with (2) α and β are easily readable as

$$\alpha=\frac{f(R)}{\varepsilon_g A\sigma F}+\frac{K_g}{\varepsilon_g\sigma F} \tag{4}$$

$$\beta=T_c^4+\frac{Cp_cT_c^{1/2}}{\varepsilon_g\sigma F}+\frac{W}{\varepsilon_g A\sigma F}+\frac{f(R)T_c}{\varepsilon_g A\sigma F}+\frac{K_gT_{CL}}{\varepsilon_g\sigma F} \tag{5}$$

Equation (3) has four solutions. For 'observable' temperature one has to look for a real positive root of (3) which should be consistent with second law of thermodynamics. For example in the present Cryo-target heat balance equation the real positive root must also satisfy the inequality $T>T_{CL.}$ It is because that even a real positive root T such that $T < T_{CL}$ indicates the violation of second law of thermodynamics. Rearranging (3) in the following form

$$T^4=-(\alpha T-\beta) \tag{6}$$

it is easy to justify that for real positive temperature 'T' , LHS of (6) must be positive. This is possible only when αT-β<0. In other words

$$0<T<\frac{\beta}{\alpha} \tag{7}$$

The range of 'T' as depicted by (7) can be written as an equation by using the trigonometric function as follows:

$$T=\frac{\beta}{\alpha}\cos\theta \tag{8}$$

where θ is real and 0 <θ < π/2. In terms of variable $\xi=\alpha^4/\beta^3$ and $z(\xi)=\cos\theta$, the heat balance equation (3) is written as

$$z^4+z\xi-\xi=0 \tag{9}$$

Once determining the real positive root of (9) the temperature of CT plate can be obtained from (8).

A number of methods are available to solve quartic equations [6],[7],[8],[9]. One obtains the following four roots for quartic equation (9):

$$z_1=\frac{1}{2}\sqrt{x}-\frac{1}{2}\sqrt{-x-\frac{2\xi}{\sqrt{x}}} \tag{10}$$

$$z_2=\frac{1}{2}\sqrt{x}+\frac{1}{2}\sqrt{-x-\frac{2\xi}{\sqrt{x}}} \tag{11}$$

$$z_3=-\frac{1}{2}\sqrt{x}-\frac{1}{2}\sqrt{-x+\frac{2\xi}{\sqrt{x}}} \tag{12}$$

$$z_4=-\frac{1}{2}\sqrt{x}+\frac{1}{2}\sqrt{-x+\frac{2\xi}{\sqrt{x}}} \tag{13}$$

where,

$$x=\frac{-8.\,3^{\frac{1}{3}}\xi+2^{\frac{1}{3}}y^2}{6^{\frac{2}{3}}y}=\frac{\mu}{\nu} \tag{14}$$

and

$$y=\left(9\xi^2+\sqrt{81\xi^4+768\xi^3}\right)^{\frac{1}{3}} \tag{15}$$

Now we examine the behavior of various roots (complex or real). Since α >0, β>0 therefore ξ>0 and hence 'y' is positive and real. Therefore 'x' is a real number. In order to know whether x>0 or x<0 we do the following algebra for μ (numerator of 'x'):

Using (15) and writing $768=2^8.3$ we write

$$\mu=-8.3^{\frac{1}{3}}\xi+8.3^{\frac{1}{3}}\xi(1+\varepsilon) \tag{16}$$

where,

$$1+\varepsilon=(\sqrt{1+\tau^2}+\tau)^{\frac{2}{3}} \tag{17}$$

and

$$\tau=\frac{9\xi^2}{\sqrt{768\xi^3}}$$

Since τ >0 therefore ε>0. Simplifying (16) we further write

$$\mu=8.3^{\frac{1}{3}}\xi\;\varepsilon \tag{18}$$

Equation (18) proves μ>0 and therefore x>0.

After proving x>0 it is easy to identify the real positive root among z_1, z_2, z_3, z_4. The reasoning's are as follows:

Since $2\xi/\sqrt{x}$ is positive (being 'x' and 'ξ') one sees that

$$-x-\frac{2\xi}{\sqrt{x}}<0$$

and therefore the roots given by z_1 and z_2 are complex and doesn't represent the real temperature. In the same footing it can be justified that the root z_3 is negative if it is real. Therefore for (3) to represent the heat balance equation for a physical heat problem the 'observable' temperature is given by

$$T=\frac{\beta}{\alpha}z_4 \tag{19}$$

In our further writing we will omit the subscript from z_4 and will simply denote it as 'z'.

A. Properties of function 'z'

Recall that z=cosθ where 0<θ<π/2 and therefore 'z' must lie between 0 and 1. The function z depends solely on a single variable 'ξ'. From (13), (14), (15) it is clear that in the limit ξ→0, z(ξ)→0. Also taking limiting behavior of y and x in terms of ξ when ξ→∞ it can be shown that the divergent parts are cancelled in (13) and z(ξ) approaches a finite value. Plot of z(ξ) is shown in Fig.2. From Fig. 2 it is clear that z asymptotically approaches 1 as ξ increases.

The derivative of the function z (z'=dz/dξ) is given as

$$\frac{dz}{d\xi}=-\frac{1}{4\sqrt{x}}\left[1+\left(1+\frac{\xi}{x^{3/2}}\right)\left(-1+\frac{2\xi}{x^{3/2}}\right)^{-\frac{1}{2}}\right]\frac{dx}{d\xi}+\frac{1}{2x}\left(-1+\frac{2\xi}{x^{3/2}}\right)^{-\frac{1}{2}} \tag{20}$$

where

$$\frac{dx}{d\xi}=-\frac{4}{y}\left(\frac{2}{3}\right)^{\frac{1}{3}}+\left[4\left(\frac{2}{3}\right)^{\frac{1}{3}}\frac{\xi}{y^2}+\frac{1}{2}\left(\frac{2}{3}\right)^{\frac{2}{3}}\right]\frac{dy}{d\xi} \tag{21}$$

and

$$\frac{dy}{d\xi}=\left(6+\frac{54\xi+384}{\sqrt{81\xi^2+768\xi}}\right)\xi y^{-2} \tag{22}$$

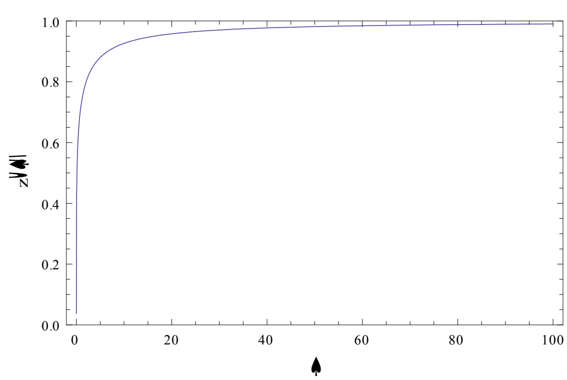

Fig. 2 Plot of z with ξ for 0 ≤ ξ ≤ 100. Note that z(ξ)lies between 0 to 1. This is true for any length of ξ such ξ>0.

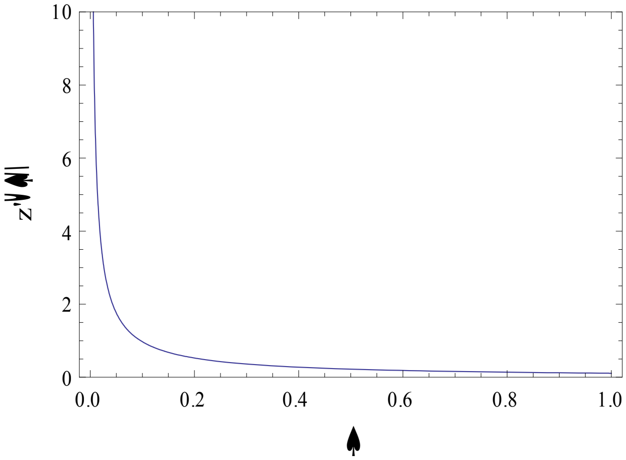

Fig 3. Plot of first derivative of z with ξ.

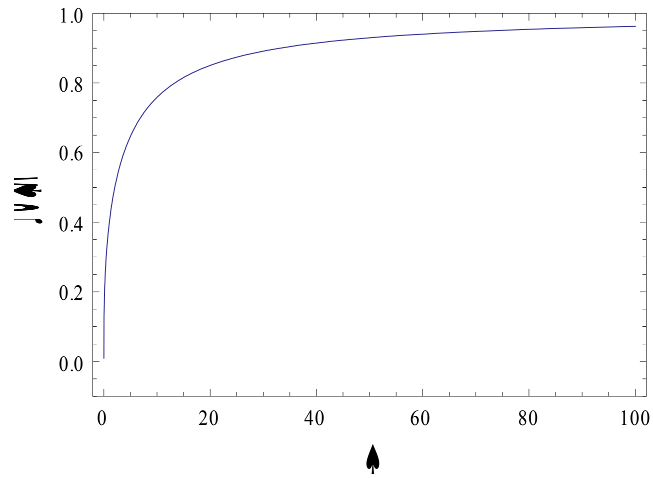

Fig. 4 Plot of $\chi(\xi)=z(\xi)-3\xi\, z'(\xi)$ with ξ.

Plot of z'=dz/dξ with ξ is shown in Fig. 3. z' has a sharp behavior near ξ equal to zero. However the function χ

$$\chi=z-3\xi\, z' \tag{23}$$

derived from z' has a smooth behavior and lies between 0 and 1 (see Fig. 4). The function 'χ' will appear in the analysis of differential variation of CT temperature with respect to changes in parameters that govern CT temperatures.

IV. THERMAL PERFORMANCE OF CRYO TARGET SYSTEM: THEORETICAL ANALYSIS

α and β contains all the parameters that govern the temperature of CT plate (see expressions 4 and 5). The term ∂T/∂δ will quantitatively describe differential variation of CT temperature with respect to a parameter δ when parameters other than δ are fixed. Here δ can be any of the parameter like T_c, p_c, T_{CL}, K_g, ε_g, F, W etc. Expression for ∂T/∂δ is given as

$$\frac{\partial T}{\partial\delta}=\left(\frac{1}{\alpha}\frac{\partial\beta}{\partial\delta}-\frac{\beta}{\alpha^2}\frac{\partial\alpha}{\partial\delta}\right)\chi+\left(\frac{\alpha}{\beta}\right)^2 z'\frac{\partial\alpha}{\partial\delta} \tag{24}$$

where the function z' and χ are given by (20) and (23) respectively.
Using expression (24) along with (20), (21), (22) and (23) one can obtain the differential behavior of CT temperature with respect to a change of a parameter 'δ' on which CT temperature depends. If one assumes ideal CT supporting arrangements so that conduction losses are neglected we can group 'δ' in two categories and study the behavior of (24). In one case $d\alpha/d\delta=0$ and in other case $d\beta/d\delta=0$. We discuss these two different cases when conduction losses are neglected.

A. Case 1: $\delta \neq K_g$

In this case $d\alpha/d\delta=0$ and equation (24) simplifies to

$$\frac{\partial T}{\partial \delta} = \frac{\chi}{\alpha}\frac{\partial \beta}{\partial \delta} \tag{25}$$

It is easy to see that $\partial\beta/\partial\delta>0$ when $\delta= T_c, p_c, T_{CL}, W$ for any fixed ε_g, A and F. Since $0<\chi<1$ and $\alpha>0$, we see that RHS of (25) is positive and therefore for this case $\partial T/\partial\delta >0$. This reflects the fact that CT temperature will always rise for any rise of T_c, p_c, T_{CL} and W when other parameters are kept fixed. Similarly CT temperature will always decreases for any decrease of T_c, p_c, T_{CL} and W when other parameters are kept fixed. For cryogenic temperatures an approximate calculation of $dT/d\delta$ can be carried out directly from equation (3). We will illustrate this in next paragraph.

Out of many $\partial T/\partial\delta$ one which is of significant important is when δ=W. If dT is the differential change in CT temperature when external heat load 'W' is change by an amount 'dW' then the quantity $\partial T/\partial W$ expresses heat load handling capacity of CT plate. Differentiating equation (3) with respect to 'W' and using values of α and β as given by (4) and (5) respectively one obtains (after neglecting conduction losses):

$$\frac{\partial T}{\partial W} = \frac{1}{A}\left(\frac{1}{4\varepsilon_g \sigma F T^3 + K_g}\right) \tag{26}$$

where T must be given from (19). CT temperature for different heat loads 'W' is shown in Fig. 5 with varying K_g.

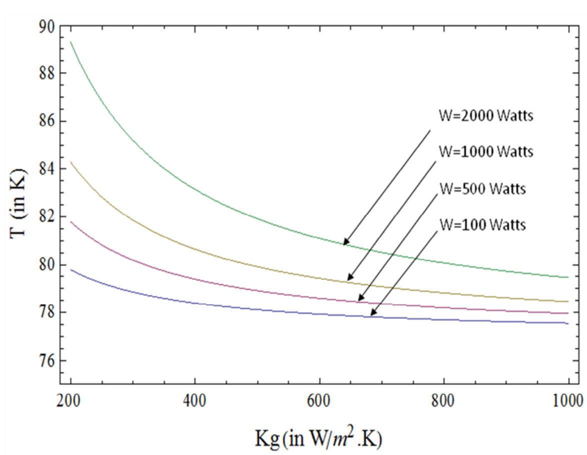

Fig. 5 Plot of CT temperature for different heat loads 'W' with K_g for T_c =300 K, T_{CL}=77K, $\varepsilon_g\times F$=1,A=1 m^2. Conduction losses and impingement power has been neglected.

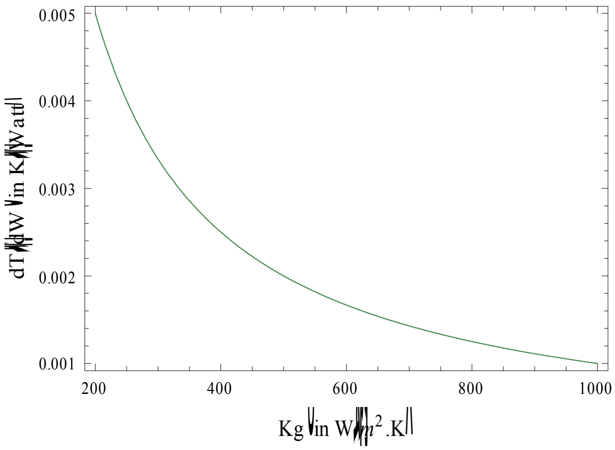

Fig. 6 Plots of CT heat load handling capacity for different heat loads 'W' mentioned in Fig. 5 with K_g for T_c =300 K, T_{CL}=77K, $\varepsilon_g\times F$=1,A=1 m^2. Conduction losses and impingement power has been neglected.Note that all plots coincide due to the fact $4\varepsilon_g \sigma F T^3 << K_g$.

Contribution of heat loads due to impingement has been neglected. From Fig. 5 it is clear that even with W=2000 Watts a unit area of CT plate can operate with LN_2 without phase change if injected with a pressure greater than 4 bar in CT with K_g>200. At 4 bar pressure LN_2 boiling temperature is around 91.2 K [10] (while $T_{CL}\approx$77 K). Variation of $\partial T/\partial W$ with K_g for different heat loads 'W' is shown in Fig. 6. Also For T $\leq$90 K, ε_g=1 and F=1 we see that $4\varepsilon_g \sigma F T^3 \leq 0.1653$. Hence this term can be neglected in comparison to K_g (say K_g>50) and we approximately have

$$\frac{\partial T}{\partial W} \approx \frac{1}{K_g A} \tag{27}$$

The approximation shown by (27) indicates that for cryogenic temperatures the heat load handling capacity of CT system is independent of CT temperature itself and solely depends upon the global coefficient of thermal exchange 'K_g'. It is clear that an increase of K_g will enhance the heat load handling capacity. In other words higher K_g of coolant provides a better stability of CT temperature with respect to variation of external heat loads caused by any other parameter. One way to obtain high K_g is to operate CT system in close loop circulation of coolant thereby maintaining a high coolant flow which increases K_g [c].
For $\delta=T_{CL}$, we have $dT \approx dT_{CL}$, in the same approximation that was used to derive (27). However this approximate equality doesn't hold when conduction losses are present in CT plates. In this case one obtains

$$dT \approx \left(1+\frac{f(R)}{K_g A}\right)^{-1} dT_{CL} \tag{28}$$

where conduction heat losses from supporting fixtures used for CT plate have been approximated as $f(R)\times(T_c\text{-}T)$ where f(R) is a function of the thermal resistance 'R 'of supporting fixtures. Equation 28 shows the fact that for stability of CT temperature T_{CL} must be held constant. For cryogenics liquids T_{CL} also depends upon their boiling point which varies under pressure. Hence during operation, cryogenics liquids must be stored in highly isolated (with respect to heat flow) and tightly tuned pressure controlled phase separators in their closed loop circulated operation.

Differential variation of CT temperature with respect to T_c can be obtained by differentiating heat balance equation. This is given as

$$\frac{\partial T}{\partial T_c} = \frac{4T_c^{\,3}}{4T^3 + \alpha} \tag{29}$$

For the case when $4T^3 << \alpha$ we simply have

$$\frac{\partial T}{\partial T_c} = 4\varepsilon_g \sigma F \left(\frac{T_c^{\,3}}{K_g} \right) \tag{30}$$

If all other parameters are constant except T_c then (30) provides an easy way to compute change in CT temperature when chamber temperature changes from T_c to qT_c. Let T_1 and T_q be the CT temperature when $T_c = T_c$ and $T_c = qT_c$ respectively. Integrating (30)

$$\int_{T_1}^{T_q} dT = \frac{4\varepsilon_g \sigma F}{K_g} \int_{T_c}^{qT_c} T_c^{\,3} dT_c$$

one obtains

$$T_q = T_1 + \frac{W_{r1}}{K_g}\left(q^4 - 1\right) \tag{31}$$

where $W_{r1} = \varepsilon_g \sigma F T_c^{\,4}$ is the radiation load on CT plate from background temperature T_c. Equation (31) helps to compute T_q if T_1 and K_g are known. Plot of $(T_q\text{-}T_1)$ with q for different values of K_g is shown in Fig. 7. It is clear from Fig. 7 that for same value of 'q' , the difference $(T_q\text{-}T_1)$ decreases with 'K_g' (as it should). Equation (31) shows that this difference is inversely proportional to 'K_g'.

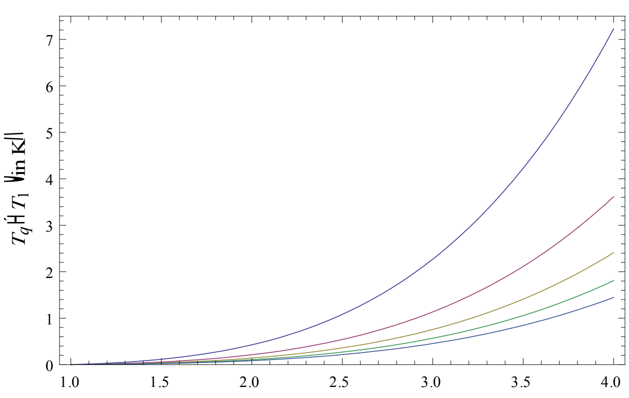

Fig. 7 Plot of $(T_q\text{-}T_1)$ with q for different values of K_g . Here T_c=100 K, T_{CL}=77 K, $\varepsilon_g \times F$=1,A=1 m^2. Conduction losses and impingement power has been neglected. In sequence of top to bottom the different curves correspond to K_g =200, 400, 600, 800, 1000 Watt/m^2.K respectively.

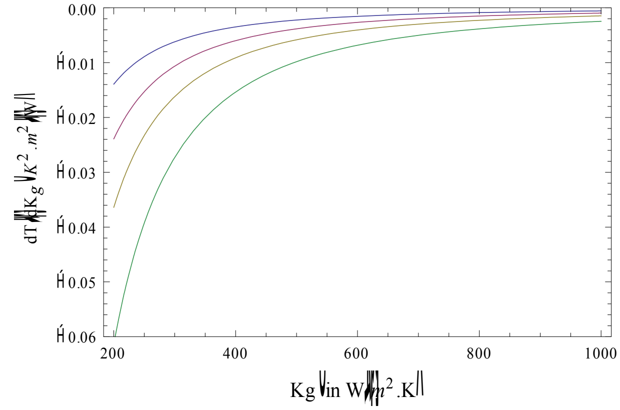

Fig. 8 Plot of dT/dK_g with K_g for different heat loads . Here T_c=300 K, T_{CL}=77 K, $\varepsilon_g \times F$=1,A=1 m^2. Conduction losses and impingement power has been neglected.In sequence of top to bottom the different curves corresponds to W= 100, 500, 1000 & 2000 Watts respectively.

B. Case 2: $\delta = K_g$

In this case both $d\alpha/d\delta$ and $d\beta/d\delta$ are non zero. Using (4) and (5), (24) is simplified to

$$\frac{\partial T}{\partial K_g} = -\left(\frac{\beta_0}{\alpha K_g} \right)\chi + \left(\frac{\alpha}{\beta} \right)^2 z^{'}(\xi)\frac{1}{\varepsilon_g \sigma F} \tag{32}$$

where conduction losses have been neglected. Also by differentiating (3) with respect to K_g, $\partial T/\partial K_g$ is obtained in terms of CT temperature as

$$\frac{\partial T}{\partial K_g} = \frac{-(T - T_{CL})}{4\varepsilon_g \sigma F T^3 + K_g} \tag{33}$$

As $T > T_{CL}$ and denominator is positive definite, (33) indicates that $dT/dK_g < 0$. This reflects the fact that by increasing K_g one always gets betterment in CT temperature. Recall that for

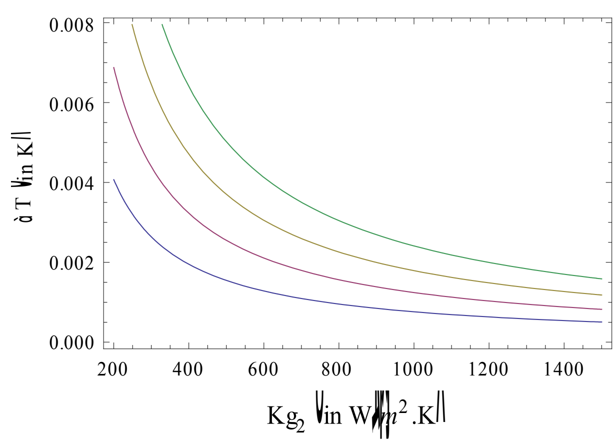

Fig. 9 Plot of ΔT with K_{g2} for different heat loads for different values of K_g . Here T_c=300 K, T_{CL}=77 K, $\varepsilon_g \times F$=1,A=1 m^2. Conduction losses and impingement power has been neglected. In sequence of top to bottom the different curves corresponds to W= 2000, 1500, 1000 & 500 Watts

respectively. Note that ΔT is of the order of mK only in the figure.

$T \le 90K$, $\varepsilon_g=1$ and $F=1$, $4\varepsilon_g \sigma F T^3 \le 0.1653$. Hence for a sufficient large K_g we have

$$\frac{\partial T}{\partial K_g} \approx \frac{-(T - T_{CL})}{K_g} \tag{34}$$

Variation of $\partial T/\partial K_g$ with K_g for different heat load 'W' is shown in Fig. 8.

With T_{CL} independent of K_g and all other parameters being fixed, it is easy to deduce from (34) that

$$T - T_{CL} \propto \frac{1}{K_g} \tag{35}$$

Whence one gets

$$\frac{T_1 K_{g1} - T_2 K_{g2}}{K_{g1} - K_{g2}} \approx T_{CL} \tag{36}$$

Where $T=T_1$ when $K_g=K_{g1}$ and $T=T_2$ when $K_g=K_{g2}$. The approximation sign (instead of equality) in (36) has been used because (34) is an approximation with the condition $4\varepsilon_g \sigma F T^3 << K_g$. Equation (36) can be written with the equality sign as

$$\frac{T_1 K_{g1} - T_2 K_{g2}}{K_{g1} - K_{g2}} = T_{CL} + \Delta T \tag{37}$$

Plot of ΔT with K_{g2} for different heat loads 'W' are shown in Fig. 9 for K_{g1}=150 W/m^2.K . From the Fig. it is clear that ΔT is of the order of milli Kelvin (mK) even for much higher heat loads. Therefore (36) is fairly accurate for practical purposes. If T_{Cl} is known, (36) can be used to find the unknown quantity if three of them are known experimentally.

CONCLUSIONS

An analytical model of flat plate Cryo-Target cooling in single phase flow have been developed for thermo-vacuum chambers. Close form expressions for differential variation of CT plate temperature under a change of system parameters are presented. Under reasonable approximations, general expressions for various important parameters related to design performance of CT plates are also derived. Specific examples for the behavior of differential temperatures of CT plates are discussed for liquid nitrogen cases.

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