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Leidenfrost Effect to Reduce Drag on Submarine

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Abstract

Heating process and boiling on a surface on which liquid falls is familiar in our daily lives, and occur in many thermally related industries. Consider a bowl or pan containing a liquid which is heated at regular intervals, the liquid will start to boil, with vapor bubbles forming at the hot surface. When it nears nucleate-boiling phase. if the surface temperature is increased further, a continuous vapour film will form that leads to the film-boiling or Leidenfrost vapor formation. We know that surface properties such as roughness and wettability can alter the transition temperature from the nucleate-boiling to transition boiling to the film-boiling phase. Leidenfrost vapor is formed at this temperature and studies have shown that it reduces drag effectively. Main focus of this analysis is to compare drag coefficient of naval bodies at STP conditions to Leidenfrost temperature (approx. 200 C) for water.

Keywords: - Leidenfrost point, Drag coefficient, Pressure and Velocity contours.

1. INTRODUCTION

Johan Gottlab leidenfrost in 1756 observed that water drops skittered on a sufficiently hot surface, due to an evaporative vapour film. Such films are stable only when the hot surface is above a critical temperature, and are a central phenomenon in boiling. However the presence of these vapour films can also reduce liquid–solid drag. Leidenfrost conducted his experiments with an iron spoon heated red-hot on the coals. After placing the drop of water into the spoon he noticed that glowing iron around the drop is darker than the rest. He deduced that "the matter of light and fire from the glowing iron is suddenly snatched into the water. “The first drop deposited in the spoon lasted for over 30 s while the next drop lasted only for 10 seconds. An additional drop lasted for a few seconds only. Observations of evaporating drops led him to a conclude that when drop vanishes "it leaves a small particle of earth in the spoon" . When droplets of water on a heated surface reach a certain temperature, the droplet surface starts to boil rapidly allowing it to float or levitate on the evaporated gas vapour. This is known as the Leidenfrost effect and is commonly seen during cooking – when sprinkling water onto a hot pan which is above the Leidenfrost point, droplets skitter across the pan and take longer to evaporate.[1]

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2. RELATED TERMS :-

Leidenfrost point

The Leidenfrost point signifies the onset of stable film boiling. It represents the point on the boiling curve where the heat flux is at the minimum and the surface is completely covered by a vapor blanket. Heat transfer from the surface to the liquid occurs by conduction and radiation through the vapor. In 1756, Leidenfrost observed that water droplets supported by the vapor film slowly evaporate as they move about on the hot surface. As the surface temperature is increased, radiation through the vapor film becomes more significant and the heat flux increases with increasing excess temperature. The minimum heat flux for a large horizontal plate can be derived from Zuber's equation

$$\frac{q}{A_{min}} = C h_{fg} \rho_v \left[\frac{\sigma g (\rho_L - \rho_v)}{(\rho_L + \rho_v)^2} \right]^{1/4}$$

where the properties are evaluated at saturation temperature. Zuber's constant, C is approximately 0.09 for most fluids at moderate pressures [2].

Heat Transfer Correlations

The heat transfer coefficient may be approximated using Bromley's equation,

$$h = C \left[\frac{k_v^3 \rho_v g (\rho_L - \rho_v)\left(h_{fg} + 0.4 c_{pv} (T_s - T_{sat})\right)}{D_0 \mu_v (T_s - T_{sat})} \right]^{1/4}$$

Where, Do is the outside diameter of the tube. The correlation constant C is 0.62 for horizontal cylinders and vertical plates and 0.67 for spheres. Vapor properties are evaluated at film temperature. For stable film boiling on a horizontal surface, Berenson has modified Bromley's equation [3].

Leidenfrost Temperature and Surface Tension Effects

The Leidenfrost temperature is the property of a given set of solid-liquid pair. The temperature of the solid surface beyond which the liquid undergoes Leidenfrost phenomenon is termed as Leidenfrost temperature. The calculation of Leidenfrost temperature involves the calculation of minimum film boiling temperature of a fluid. Berenson obtained a relation for the minimum film boiling temperature from minimum heat flux arguments. While the equation for the minimum film boiling temperature, which can be found in the reference above, is quite complex, the features of it can be understood from a physical perspective. One critical parameter to consider is the surface tension. The proportional relationship between the minimum film boiling temperature and surface tension is to be expected since fluids with higher surface tension need higher quantities of heat flux for the onset of nucleate boiling. Since film boiling occurs after nucleate boiling, the minimum temperature for film boiling should have a proportional dependence on the surface tension. Henry developed a model for Leidenfrost phenomenon which includes transient wetting and microlayer evaporation. Since the Leidenfrost phenomenon is a special case of film boiling, the Leidenfrost temperature is related to the minimum film boiling temperature via a relation which factors in the properties of the solid being used. While the Leidenfrost temperature is not directly related to the surface tension of the fluid, it is indirectly dependent on it through the film boiling temperature. For fluids with similar thermophysical properties, the one with higher surface tension usually has a higher Leidenfrost temperature. For example, for saturated water-copper interface, the Leidenfrost temperature is 257 °C (495 °F). The Leidenfrost temperatures for glycerol and common alcohols are significantly smaller due to their lower surface tension values (density and viscosity differences are also contributing factors.) [4]

3. PURPOSE AND METHODOLOGY

In the naval system, water transport bodies like heavy ships, cruises and especially submarines have to deal with plenty of drag offered by water which is mostly comprising of skin friction coefficient. From the above Drag reduction by Leidenfrost vapor layer this can be employed to a submarine (military submarines) . They require to move a much higher speed which is rather a mere speed of 40 -45 knots. This can be done in following ways :-

PRE ANALYSIS ON PROTOTYPE OF SUB-MARINE

For analysis purpose we use ANSYS WORKBENCH software to pre analyse it

and to observe reduction of drag on submarine when it is elevated to film boiing temperature of water.

GEOMETRY AND MESHING

Meshing is done to the geometry after creating an enclosure(acts as boundary domain) and then subtracting enclosure from geometry by Boolean operations for limiting our drag coefficient finding to submarine body.

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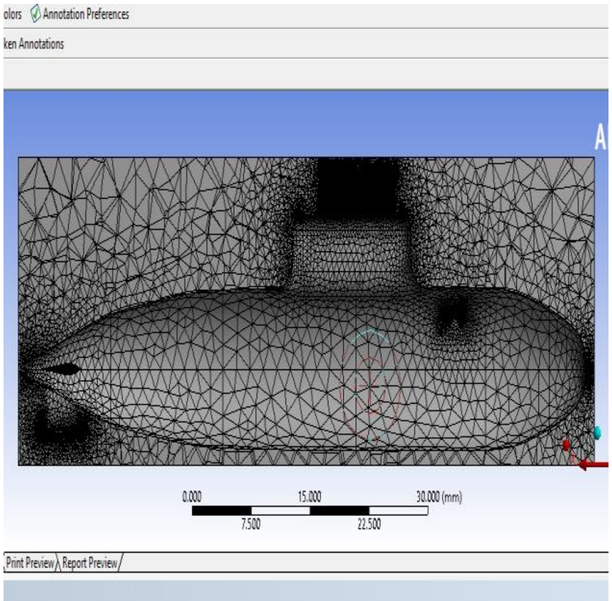
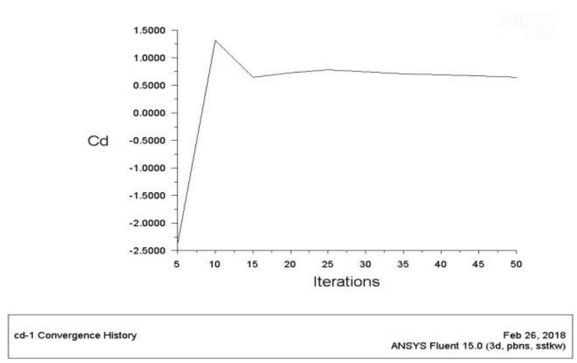


We then suppress the half part of geometry and other half of geometry is then undertaken for simulation purpose as symmetry exists between XY plane .Then MESHING is done to obtain analysis of finer details around submarine. Care must be taken that skewness must be lesser or equal to 0.9 . Again refinement and inflation layer can be created ,but shouldn't be at cost of limiting skewness. Named selection is given as IN(inlet of water),OUT(outlet of water),WALLS (4 boundary walls

4. DRAG RESULTS

After plotting Cd (coefficient of drag) of sub marine results are compared at different temperatures of 300 K and 473 K.

We find that initially Cd is very low for 300 K which equals approximately -2.3 which compares to 1.4 of 473 K but after 9 iteration that's were the contrast stops and leidenfrost vapor kicks in and drag reduces drastically since then. We have limited our iteration to 50 as drag almost remains constant between (0.6-0.75) for 300 K .However drag decreases drastically for 400 K



Cd values at 300 K

to 0.64 from 1.14 and continues to decrease further. The value of Cd at 473 K is initially 1.4 and keeps decreasing to minimum value of 0.61 and continues to decrease further.

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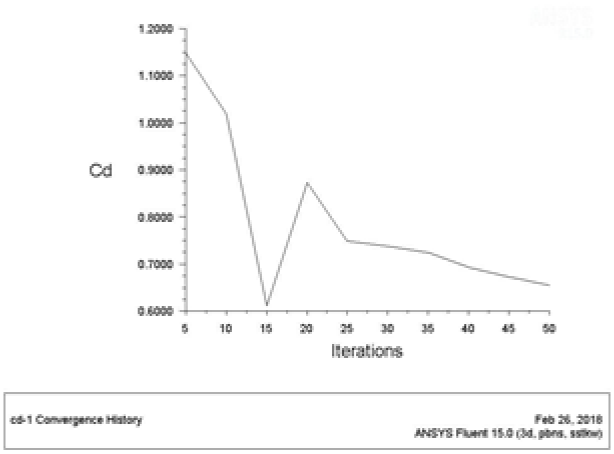
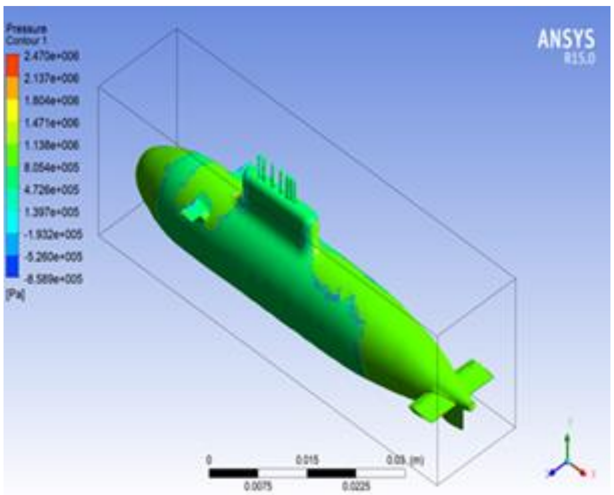


Cd values at 473 K

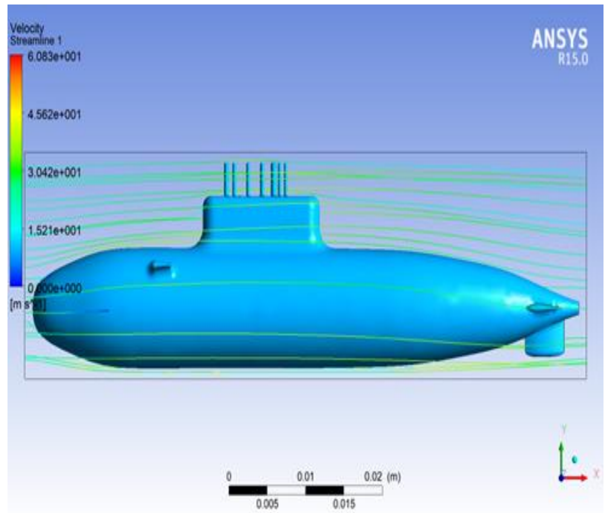


CONTOURS COMPARISION

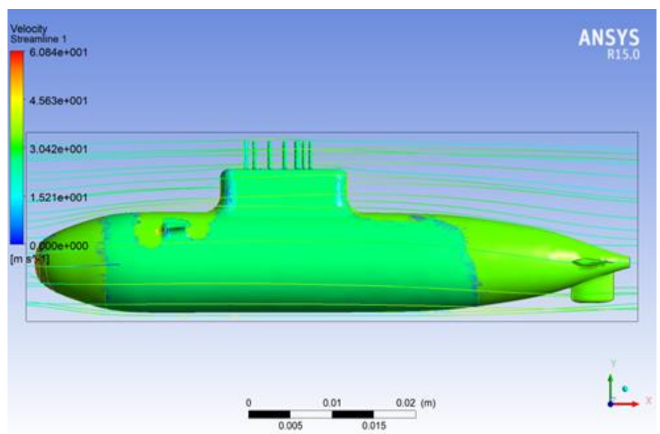
Submarine in both cases experiences pressure force applied by water which then accounts for drag force . Contours of pressure is shown above.In this same amount of force applied by water, submarine at 473k achieves higher speed due to reduction in drag which is then due to leidenfrost vapor. Below is comparision between velocities attained at 300 K and 473 K

VELOCITY CONTOURS

From comparing figures directly we can say that velocity of sub-marine at 473K is higher than that of sub-marine at 300K



VELOCITY CONTOUR AT 300K



VELOCITY CONTOUR AT 473K

5. ARTIFICIAL COATINGS TO ACHIEVE OR REPLICATE LEIDENFROST VAPOR

Novel methods to reduce hydrodynamic drag are crucial to efficient energy usage with applications from naval architectural design to the operation of microfluidic devices. One innovative approach to achieve drag reduction on a solid body moving in liquid is to introduce a lubricating gas layer between the body surface and the surrounding liquid by deploying textured superhydrophobic surfaces , micro bubble injection , polymer additives etc. Also cryogens can be used which is first tested and this is leidenfrost cold phenomenon different from leidenfrost hot phenomenon

6. CONCLUSION

Our study shows that drag is more initially for a submarine at leidenfrost temperature compared to STP conditions of water. But eventually after short span of time it decreases continuously and effectively. Drag is reduced effectively when submarine is elevated to leidenfrost temperature which is to be practically achieved and stabilized by above artificial methods mentioned.

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