AERODYNAMIC STUDY OF EXHAUST SMOKE – SUPERSTRUCTURE INTERACTION ON NAVAL SHIPS

by

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CERTIFICATE

This is to certify that the thesis titled "**AERODYNAMIC STUDY OF EXHAUST SMOKE-SUPERSTRUCTURE INTERACTION ON NAVAL SHIPS**" being submitted by **PRAMOD R. KULKARNI** is report of bonafide research work carried out by him under our supervision. This thesis has been prepared in conformity with the rules and regulations of Indian Institute of Technology, New Delhi, India. We further certify that the thesis has attained a standard required for a Ph.D. degree of the Institute. The research reported and results presented in the thesis have not been submitted, in part or full to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

The contamination from smoke discharged from ships funnel has been found to manifest itself in the form of objectionable quantities of smoke coming down on topside operational areas. This is a problem for almost all vessels, regardless of type – be it the passenger liners, merchant ships or the naval ships. On naval ships, particularly frigates, destroyers and aircraft carriers, the problem of smoke nuisance manifests itself as interference of exhaust gases with normal aircraft operations, exposure of the various topside operational areas, ventilation openings, electronics and weapon systems to hot exhaust gases and therefore, to high temperature and contamination, rise in the intake air temperature of the gas turbines due to the exhaust gases coming out of the funnels being sucked into GT intakes and the susceptibility of the ships to the IR (infrared) guided anti-ship missiles because of high temperature of the exhaust and its impinging on the superstructure, thus resulting in increased infrared signature. Ship superstructures of modern naval ships are geometrically much more complex as compared to their predecessors or the counterparts in the passenger or the cargo ships as they feature many appendages which are aerodynamically bluff bodies, like masts, superstructure/bridge blocks etc. The funnel competes for topside space and weight with densely packed weapons and sensors, and the greatly reduced funnel heights sometimes make it difficult to distinguish the funnel in the profile. The tendency of modern naval ships to favor very short funnel heights results in violation of good design practices of a funnel for avoiding smoke nuisance (like increasing funnel height and avoiding the bluff bodies in the vicinity of the funnels), thereby making them prone to the problem of smoke nuisance.

Though the "smoke nuisance problem" has been a subject of study and research since late 1940's, the data and publications regarding the exhaust smoke-superstructure interaction on naval ships is ***classified*** and ***restricted*** and is not

available in open literature. Warship design is a complex exercise. The understanding of dispersion of exhaust smoke is an important aspect of ship design that falls under the category of aerodynamics. However, very often, the application of aerodynamics is not recognised a priori in the design of ships. Traditionally, the exhaust smoke superstructure interaction and the funnel performance has been investigated using scale models in wind tunnel at a relatively advanced stage of design. However, in order to take the smoke nuisance problem into account, the ship designer needs to be able to have a means of visualising the path of the exhaust under different conditions very early during the design phase. This experimental and numerical study of the exhaust smoke-superstructure interaction is envisaged to fulfill such a need.

An aerodynamic study of the exhaust smoke-superstructure interaction on naval ships is carried out for a simplified superstructure of a generic frigate shape. The phenomenon of interest is the near-field smoke dispersion in the flow field that is disturbed by bluff bodies of the superstructure in the vicinity. In the near field, the plume path is inertia dominated rather than buoyancy dominated and therefore, in the present study, the buoyancy forces are ignored in the simulation. As a first step, scale model experimentation in wind tunnel with wind conditions scaled accordingly without considering the thermal gradients to measure and study the behavior of the interaction between funnels and the ship deck structures is undertaken. This has been done by simulation of the flow over a model ship superstructure in the wind tunnel and injection of iso-thermal (unheated) exhaust flow from the funnels of the model superstructure. This study includes the mapping of the flow structure around simplified representative superstructures of a generic frigate using the 3-hole probe as well as the flow visualisation studies (by smoke technique) for some practical ship situations and configurations.

The flow visualisation studies undertaken on four variants of superstructure configurations at different flow conditions provide high quality photographs of the plume trajectories. Apart from providing an insight into the interaction of exhaust smoke and the superstructure on naval ships, these photographs enable a qualitative comparison of the plume trajectory predicted by CFD. The mapping of the flow structure for three different operating conditions in the wind tunnel through velocity measurements with a total of 7560 discrete measurements at 12 measurement planes which are chosen so as to cover the most critical flow region around the superstructure has resulted in generation of a large body of benchmark experimental data and obtaining the physical quantities that can directly be correlated to the results of the numerical simulations. Practicing Engineers do not generally accept CFD results without some amount of experimental validation. The methodology adopted in the present study involves comparing the flow parameters predicted by CFD simulation using the CFD code FLUENT version 6.0 with experimental results from the wind tunnel study. The comparison of the experimental data (from flow visualisation studies as well as mapping of the flow structure in the wind tunnel) with the results from CFD simulation show a reasonably good agreement which leads to the conclusion that the numerical scheme, wherein the closure is achieved by using the standard k-ε turbulence model along with grid refinement and grid adaptation techniques, predicts the flow and performance characteristics reasonably well.

After having established that the capability of the standard k-ε turbulence model to predict the flow and performance characteristics around the ship's superstructures by displaying a reasonably good agreement between the predicted and the experimental results, the same turbulence model and solving techniques are used for undertaking parametric investigation of the aerodynamic study of the exhaust smoke-superstructure interaction on the ship's topside. The prediction of flow path of the exhaust plume from the ship funnels is extremely complicated since the phenomenon is affected by a large number of parameters like wind velocity and direction, level of turbulence, geometry of the structures on the ship deck, efflux velocity of smoke etc. To complicate the matters, the entire turbulent flow pattern is subject to abrupt changes as the yaw angle changes. The parametric investigation using CFD is carried out by varying the velocity ratio (K), yaw angle (ψ) and the superstructure configuration. A total of 112 cases are investigated.

Based on these wind tunnel and CFD studies, the following conclusions are drawn:

a) The air wake of the superstructure of a naval ship contains significant gradients in mean wind speed and direction, as compared to those of the natural wind. Further, the presence of a bluff body induces a modification in the undisturbed velocity field, originating vortical structures downstream of the body whose form, dimension and persistence are a function of the size and location of the bluff body.

b) Turbulent eddies caused by the interaction of the wind with bluff body superstructure as well as the smoke funnel itself are found to cause a downwash of the smoke.

c) Momentum increase is necessary to clear the plume from the wake of a funnel or superstructure and prevent the downwash. It is concluded from the study of all the configurations of superstructure taken up for investigation by flow visualisation in the wind tunnel as well as the parametric investigation by CFD that a velocity ratio of at least 2 should be maintained to avoid the problem of downwash.

d) The performance of the funnel exhaust in the wind is found to degenerate at the yaw angles between 20° to 30° in all the configurations of the superstructure investigated and therefore, these may be termed as adverse range of yaw angles as far as downwash from funnels is concerned.

e) It is strongly recommended that the ship designer should specially study the flow conditions with relative winds over the adverse range of yaw angles and the low velocity ratios, which would be the critical design conditions. Further, at the critical conditions (of low velocity ratios and adverse yaw angles), it is the funnel gas momentum that has a much more dominant effect as compared to exhaust gas buoyancy in determining the plume trajectory as well as whether the ingress into GT intake will be a problem.

f) This study has conclusively demonstrated that CFD is a powerful tool capable of accurately predicting the larger scale features of the exhaust smoke-superstructure interaction on naval ships as long as sufficient care is taken to ensure the fineness of the grid used in the analysis.

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