Applied Ocean Research 48 (2014) 176–185

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

Experimental and numerical investigation of air entrainment into a louvred funnel

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ARTICLE INFO

Article history:
Received 23 March 2014
Received in revised form 10 July 2014
Accepted 21 August 2014
Available online 16 September 2014

Keywords:
Louvred funnel
Jet
Ship
CFD
Entrainment
Infrared

ABSTRACT

In the present study, experiments as well as numerical computations based on finite volume method have been carried out to investigate the entrainment of ambient air into a laboratory-scale louvred funnel, which are mostly used in naval warships and cargo ships to suppress infrared emissions. Conservation equations for mass, momentum and energy are solved in a three-dimensional domain by employing eddy viscosity based two equation $k-\varepsilon$ turbulence model with log-law wall functions. Reynolds number, louvred opening area as well as nozzle protruding length are varied in the range of $3250 \le R_e \le 6600$, $116.7 \le A_L/D_{\mathrm{nz}}^2 \le 584$, and $0 < L_p/D_{\mathrm{nz}} < 12$, respectively. It is observed that the mass suction increases with the Reynolds number, louvred opening area and nozzle protruding length. The louvred opening-area is the most important parameter in the entrainment process and then, the nozzle protruding length is the second most affecting parameter on air suction. Experiments using hot nozzle fluid are conducted to establish the fact that hotter fluid will always entrain more surrounding air compared to the cold nozzle fluid because of buoyancy. It is also observed that the computed and experimental values of mass entrainment rates agree well with each other.

1. Introduction

It has become necessary to investigate the mass entrainment into a louvred funnel (used on naval ships) owing to growing demand for infrared stealth technology. Many gas turbine installations, such as warships or naval ships use louvred funnel to cool the exhaust gas expelled from the turbines before they are ejected to the atmosphere. Hence, for a warship, the use of louvred funnels is very much essential to reduce the temperature of the hot combustion product from the gas turbine. If the hot gas is exhausted to the atmosphere without cooling, then the ship can be tracked in the deep ocean. This can be strategically a wrong decision for the ship operation in the deep ocean. Therefore, a louvred funnel is used to entrain ambient air into it so that the hot combustion product coming out of the turbine exhaust can be mixed with the cold air to cool it. The louvred funnel is called passive device, as it requires no power to entrain the fresh ambient air. Hence, the operation of a louvred funnel is hassle free with almost no expenses to maintain it.

In the past, ejector–diffuser or lobed infra-red suppressor systems were used to cool the combustion products by entraining and mixing ambient air with it. In case of lobed infrared suppressor, an improved mixing process had been reported by Werle et al. [1]. Thus, in a lobed infrared suppressor, a higher entrainment rate is obtained. An attempt has been made by them to compare the mixing caused by a forced lobe mixer and normal shear mixing. McCormick and Bennett [2] supported Werle et al. [1] and demonstrated that such lobes introduce shear flow instabilities into the mixing process, which further enhances the mixing and entrainment. These lobed infrared suppressors, in general, are installed at the tail pipe of aircrafts and helicopters so as to augment the propelling thrust as well as to reduce the infrared radiation.

The study of the infrared (IR) signature from the exhaust of aircrafts and helicopters have been carried out by various researchers, such as Panton and Warnes [3], Bettini et al. [4], Shan and Zang [5], Liu et al. [6] and Riqitai et al. [7] to name a few. Mahulikar et al. [8] studied the effect of sky, sun as well as earth radiation on an aircraft IR signature. The effect of by-pass ratio on the IR signature from aircraft exhaust was modelled by Rao et al. [9] and Chen et al. [10]. They studied the impact of helicopter skin temperature on its IR characteristics. Brik and Vandam [11] carried out a parametric study of a 1/4 scale DRESS Ball IRSS device and compared the results with a full scale sea model. A DRESS Ball IRSS device has been installed on the exhaust of a GE LM2500 gas turbine. The parameters such as metal surface temperature, back pressure, plume temperature, and static pressure distributions have been

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http://dx.doi.org/10.1016/j.apor.2014.08.009

considered in their study in order to reveal the effect of each parameter on infrared radiation. Thompson et al. [12] discussed possible methods such as use of special paints to conceal the hot spots and installation of IRSS devices at the exhaust of a gas turbine to reduce the plume temperature.

A very few studies have been carried out to measure the entrainment into louvred funnels installed on the naval or cargo ships. The entrainment rate into an infrared suppression device has been carried out by Barik et al. [13,14]. A computational study has been carried out by Mishra and Dash [15], Mishra and Dash [16] to investigate the mass suction into a louvred funnel. Valuable information on entrainment rate has been acquired from their study. However, their study was lacking the experimental validity of the results. The present study is carried out because of following reasons:

(a) Lack of experimental basis to investigate the mass suction into a louvred funnel.
(b) In the previous studies, multiple diffuser rings have been employed to construct an infrared suppressor. Since these diffuser rings need to be installed inside the aft and the foreword funnels of a ship, these may affect the dynamic stability of a ship. However, the stability problem of the ship is reduced in the present louvred funnel as single louvred funnel has been employed for the entrainment process.
(c) A parametric study has been carried out by Mishra and Dash [15] without having a clear physical explanation of the flow recirculation in the suction zone. The flow recirculation is an important phenomenon in the design of louvred funnels in real-life situations.

Experiments with hot nozzle fluid have not been carried out yet in order to investigate its effect on the entrainment rate by a louvred funnel. Hence, we carried out this study on a laboratory scale louvred funnel to investigate the mass suction as well as the physics of the entrainment process. An attempt has also been made to demonstrate the flow circulation inside the louvred funnel.

2. Experiment

2.1. Experimental setup

The schematic diagram of the experimental facility and its snapshot are shown in Fig. 1(a) and (b), respectively. In the present study, a cylindrical funnel made up of Perspex sheet is used. Five rows of circular louvres and each of these rows containing twelve louvres are cut on the peripheral surface of the funnel, which is placed on an iron stand at the exit of the nozzle. Surrounding air may be sucked and mixed with the hot air emanating from the nozzle exit. In the present experiment, three different funnel diameters ($D_f/D_{\mathrm{nz}} = 11.2, 16, 19.2$) have been used. A double wall rectangular duct heater equipped with seven fin-type heaters (each of 500 W) supplies air to the nozzle. A rectangular heater (inner duct size 1 m × 0.3 m × 0.3 m) is used to heat the air. The annular space between inner and outer duct is packed with glass wool insulation to prevent the leakage of heat. The local outlet temperature is measured by placing nine RTD type temperature sensors on the exit plane of the louvred funnel. A radial distance of 0.01 m is maintained between any of the two sensors. A sensor is located at the centre of the nozzle, which is used to measure the temperature of outgoing air. The installation of multiple sensors is discarded as the diameter of the nozzle is very small. All the temperature sensors are calibrated using a thermostatic bath (Julaboo make) in order to ensure the temperature accuracy within ±0.5 °C. Utmost care has been taken to measure the exit velocity of the louvred funnel with a hot wire anemometer (Model 8345 and TSI make).

2.2. Experimental procedure

The air from the storage tank of a compressor (Fig. 1(a)) is allowed to enter the duct heater, via a flow control valve, which can monitor 150 L/min of flow by a rotameter. This air is heated in the duct heater in case of experiments on hot air are to be performed. The cold or hot air enters into the funnel (vertical upward direction) from a metal nozzle of diameter and length, 1.25 cm and 5 cm, respectively. In the present case, since the length to diameter ratio is very small ($L_{\mathrm{nz}}/D_{\mathrm{nz}} = 4$), a uniform velocity profile is expected at the nozzle exit. The mass flow rate, and hence, the nozzle exit Reynolds number is varied by placing a flow control valve before the rotameter. Reynolds number (based on the nozzle diameter) and nozzle exit temperature variations are maintained in the range $3250 \le Re \le 6500$ and $1 \le T_{\mathrm{nz}}/T_\infty \le 1.18$, respectively. Throughout the investigation, special care has been taken to ensure that the experimental facility is isolated from any external disturbances to minimize their effect on the mass entrainment. The ambient temperature is considered isothermal at 30 ± 0.5 °C. The nozzle exit velocity is measured at four different locations using a hot-wire anemometer. Similarly, on the exit plane of the funnel, the local velocity is measured at nine different locations. To ensure correct measurement of velocity, the probe of the hot-wire anemometer is kept perpendicular to the air flow as shown in Fig. 1(a). The nozzle inlet mass flow rate $\dot{m}_{\mathrm{in}}$ and the mass flow rate at the exit of the IRS device ($\dot{m}_{\mathrm{out}}$) are calculated by integrating the local mass flow rates as follows:

$$\dot{m}_{in} = \int_0^{r_{\mathrm{nz}}} 2\pi r \rho(T) V(r) dr \tag{1}$$

$$\dot{m}_{\mathrm{out}} = \int_0^{r_{\mathrm{tf}}} 2\pi r \rho(T) V(r) dr \tag{2a}$$

$$Re = 4 \times \frac{\dot{m}_{\mathrm{in}}}{\pi \times \mu \times D_{\mathrm{nz}}} \tag{2b}$$

The entrainment rate into the IRS device is computed as:

$$\dot{m}_{\mathrm{suc}} = \dot{m}_{\mathrm{out}} - \dot{m}_{\mathrm{in}} \tag{3}$$

In this particular context, the source of error in the experimental measurements is the measurement of the length with a scale, the velocity measurement by an anemometer and the inlet flow measurement by a rotameter. An uncertainty analysis has been performed for each of these measurements, as suggested by Klein and McClintock [17]. The uncertainty in the mass suction is found to be around 1–2.0%, and the details of the experimental uncertainty can be seen in Figs. 6, 8, 9 and 13–15.

3. Mathematical formulation

In this study, a three dimensional computational domain (geometrically exact to the experiment) is considered as shown in Fig. 2(a). The mesh configuration on the louvred funnel is shown in Fig. 2(b). In order to entrain ambient air into it, a cylindrical computational domain of same height as that of the louvred funnel is placed around it as shown in Fig. 2(c).

A cylindrical computational domain of diameter 20 times that of the nozzle diameter should be used as suggested by [18] so that the air entrainment from surrounding may not be affected by this enclosure. Also, Mishra and Dash [16] have used a similar computational domain in their study on louvred funnel. In our case, a cylindrical computational domain of diameter 50 times bigger than the diameter of the nozzle is placed around the louvred funnel.