A Study on the Heat Flow Characteristics of IRSS

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Abstract. The infrared signatures emitted from the hot waste gas generated by the combustion engine and generator of a naval ship and from the metal surface around the funnel are the targets of the enemy threatening weapon system, thereby reducing the survivability of the ship. Such infrared signatures are reduced by installing an infrared signature suppression system (IRSS) in the naval ship. An IRSS consists of three parts: an eductor that creates a turbulent flow in the waste gas, a mixing tube that mixes the waste gas with the ambient air, and a diffuser that forms an air film using the pressure difference between the waste gas and the outside air. This study analyzed the test model of the IRSS developed by an advanced company and, based on this, conducted heat flow analyses as a basic study to improve the performance of the IRSS. The results were compared and analyzed considering various turbulence models. As a result, the temperatures and velocities of the waste gas at the eductor inlet and the diffuser outlet as well as the temperature of the diffuser metal surface were obtained. It was confirmed that these results were in good agreement with the measurement results of the model test.

1. Introduction

Due to the changes in the global security environment and the dramatic advances in maritime weapon systems, the modern battlefield environment in the ocean exhibits various complexities. To overcome these complexities, technologies related to special performances for survivability have been improved [1]. Such technologies include radar cross section (RCS), which determines the size, direction, and distance of a naval ship by detecting the energy of the electromagnetic waves that were radiated from the radar and reflected by the naval ship, underwater radiated noise (URN), which detects mechanical noise emitted from a ship to the surrounding fluid, and infrared (IR), which detects the heat energy emitted from the surface of a naval ship.

As for the studies related to the IR stealth technology, a study has been conducted on the calculation of the IR signatures from a naval ship and the sensitivity analysis of the marine environmental variables [2], and studies on the measurement and verification of the IR from the actual naval ships have been conducted to secure the reliability of analytical results [3]. In addition, the establishment of the reference marine environmental conditions for signature analysis [4] and the effect of the waste gas on the infrared signatures of a naval ship [5] were also studied. There have been also many studies on the equipment development for reducing IR signatures from a naval ship, and studies on the development of analysis software that can calculate IR signatures more accurately have been consistently conducted [6].

The IR signature reduction systems for naval ships include the hull seawater cooling system, which reduces the contrast radiant intensity (CRI) against the surroundings by spraying seawater onto the hull of a naval ship, and the IRSS, which reduces the hot waste gas by optimizing the shape of the waste pipe. An IRSS consists of three parts: an eductor that creates a turbulent flow in the waste gas, a mixing tube that mixes the waste gas with the ambient air, and a diffuser that forms an air film using the pressure difference between the waste gas and the outside air.
This study analyzed the test model of the IRSS developed by an advanced company and, based on this, conducted heat flow analyses as a basic study to improve the performance of the IRSS. For the heat flow analysis, a commercial analysis program was used and the results were compared and analyzed considering various turbulence models.

2. Model test
Manufacturers produce a miniature model with the same geometry as the actual system and conduct a performance test to verify the performance of a designed IRSS. In this instance, the main performance evaluation items include the back pressure applied to the engine, the temperature of the waste gas, and the metal surface temperature of the waste pipe. The temperature, static pressure, and total pressure of the waste gas that is flowed in the equipment are measured using Pitot tubes at the eductor inlet and the diffuser outlet to verify the test conditions and results. Figure 1 shows the schematic diagram of the IRSS covered in this study.

![Figure 1. Schematic of IRSS.](image)

The Pitot tubes are placed in the transverse direction of the eductor inlet and the diffuser outlet, and measures the temperature, static pressure, and total pressure at the same time. The measurement positions of the Pitot tubes are 21 points at the eductor inlet and the diffuser outlet, respectively. The areas of the eductor inlet and the diffuser outlet are divided into five equal areas and the measurement was performed in the up, down, left, and right directions. The metal surface temperature of the waste tube is measured through the temperature measuring instruments that use thermocouples, which were welded on both ends of each diffuser ring at 5mm intervals. The IRSS has five diffuser rings and the number of the temperature measurement points is 20 in total.

Once the system for test evaluation is constructed, the IRSS model is connected to the thermal wind tunnel tester and the heat flow conditions are set. The operation is maintained for a certain period of time until the measurement values are stabilized, and then the stabilized measurement values are recorded. Table 1 shows the test conditions of the miniature model [7].

| Mass flow [kg/s] | Gas Temperature [°C] | Gas Density [kg/m³] |
|-----------------|----------------------|---------------------|
| 1.55            | 525                  | 0.4424              |

3. Heat flow analysis
In this study, STAR-CCM+ 11.02, software for flow analysis, was used. For more precise analysis, a 3D analysis model was implemented using the 3D shape modification function and the automatic mesh creation function provided by the software.
The continuity equation and the Reynolds averaged Navier-Stokes (RANS) equation used as the governing equations of the flow analysis are as shown in equations (1) and (2), respectively.

\[
\frac{\partial \rho u_i}{\partial x_i} = 0
\]  
\[
\rho \frac{\partial u_i}{\partial x_j} = \rho f_i + \frac{\partial}{\partial x_j} \left[ -\bar{p} \delta_{ij} + \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \rho u_i u_j \right]
\]

In the equations, \( \overline{u_i} \) is the velocity in each direction in the Cartesian coordinate system, \( \rho \) the density, \( f_i \) the mean volume force, \( \bar{p} \) the isotropic pressure, \( \delta_{ij} \) the deformation of the fluid particle, and \( \mu \) the friction coefficient [8]. The last term in equation 2 is the Reynolds stress, which refers to the shear stress generated by turbulence. In this study, K-Epsilon, shear stress transport (SST) K-Omega, Reynolds stress turbulent (RST) models were applied as turbulence models to obtain the Reynolds stress, the results of each model were compared and analysed.

The domain for the heat flow analysis was set large enough to prevent the energy from being accumulated in the domain and affecting the analysis results. In other words, the length of the domain was set to 100 times the diameter of the diffuser tip and the width was 50 times the diameter of the diffuser tip. Structured grids were used in the gas region of the domain, and approximately six million grids were created around the IRSS by increasing the grid density. In the solid region of the domain, about 150,000 polyhedral grids were created using polyhedrons with 12-16 faces to reduce the analysis time. If structured grids are used in the solid region corresponding to the thin plate in the analysis model, too many grids can be created, which significantly increases the analysis time. Figure 2 shows the magnified part of the created grids.

![Figure 2. Grids of analysis domain.](image)

4. Analysis results

4.1. Waste gas temperature
The numerical analysis results of the temperature and velocity of the waste gas at the eductor inlet were compared with the test results and were shown in figure 3. In this study, the temperature and velocity error rates of the turbulence model at the eductor entrance compared to the test measurement values were minimized by creating polynomial functions from the test measurement values and setting them as the initial conditions of the numerical analysis. The temperature and velocity at the eductor inlet were highest in the center of the eductor. This is because the flow created by the thermal wind tunnel tester gradually changed into a fully developed flow, resulting in the highest flow velocity in the center and the temperature increase due to convection.
The numerical analysis results of the temperature and velocity of the waste gas at the diffuser outlet were compared with the test results and were shown in figure 4. The temperature and velocity in the radial direction were similar to those at the eductor inlet, but the error rates of the turbulence model compared to the test measurement values were relatively high. In this study, the results of the K-Epsilon model, in which the maximum error rates of the temperature and velocity were 8% and 21%, exhibited best agreement with the model test results.

4.2. Metal surface temperature of the diffuser

The spray pattern of the hot waste gas varies depending on the shape of the eductor outlet. The eductor outlet in this study had the lobe shape and the temperatures of the mixing tube and the diffuser metal surface caused by the waste gas sprayed from the eductor are shown in figure 5(a). When the hot waste gas passes through the diffuser, the low-temperature outside air is introduced inside through the diffuser ring gap due to the pressure difference. In this case, the temperature of the lower portion of the diffuser ring is relatively decreased compared to the upper portion. Figure 5(b) shows the velocity vectors of the outside air introduced through the diffuser ring gap. Unlike the analysis results, the temperature difference between the upper portion and lower portion of each ring was not clear in the test results that used thermocouples.
5. Conclusion
This study is a basic study to investigate the heat flow characteristics and improve the performance of the IRSS for naval ships. Below are the results of the heat flow analysis.

1) The test model of the IRSS developed by an advanced company and installed in naval ships were analyzed and the heat flow analysis conditions were identified.

2) Various turbulence models were applied to the heat flow analysis and the results of each analysis were compared and analyzed. In this study, the results of the K-Epsilon model, among the turbulence models, exhibited best agreement with the model test results.

3) Through the heat flow analysis, it was possible to identify the phenomena including the temperature distribution in the diffuser ring caused by the outside air introduction effect, which could not be observed by the model test results alone.

6. References
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