A Study on the Characteristics of Design Variables for IRSS Diffuser

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Abstract. In modern naval ships, infrared signature suppression systems (IRSS) are installed to decrease the temperature of waste gas generated in propulsion engine and the metallic surface temperature of heated exhaust pipes. Generally, IRSS is composed of eductor, mixing tube, and diffuser. Diffuser serves to reduce the temperature by creating an air film using the pressure difference between internal gas and external air. In this study, design variables were selected by analyzing the diffuser and the characteristics of design variables that affect the performance of diffuser were examined using Taguchi experiment method. For the diffuser performance analysis, a heat flow analysis technique established in previous research was used. The IRSS performance evaluation was carried out based on the average area value of the metal surface temperature and the temperature of the exhaust gas at the outlet of the diffuser, which are variables directly related to the intensity of infrared signature in naval ships. It was verified that the exhaust gas temperature is greatly affected by changes in the diameter of the diffuser outlet, and the metal surface temperature of diffuser is greatly affected by changes in the number of diffuser rings.

1. Introduction

Advanced naval powers are establishing plans for the development and building of new naval ships through in-depth analysis of operational requirements for future naval battles and development trends of military science and technology [1]. In Korea, special performance technologies started to be applied from the 1990s during naval ship design for survivability improvement. In the 2000s, research on infrared stealth technologies started to be conducted through the acquisition of advanced foreign technologies [2].

Studies on infrared signature suppression systems (IRSS) include a research on the optimization of nozzle shape for infrared signature reduction in the field of aviation [3], a research on the identification of critical design factor of DRES-Ball type IRSS [4], a research on the classification of infrared signature sources in naval ships and its reduction [5], and a research on the development of analysis software that can provide more precise calculations of infrared signature of naval ships [6]. Almost researches are limited to the subjects of calculation and evaluation of infrared signature because the design of IRSS is a security related subject.

The types of IRSS developed in advanced companies are Cheese Grater type, Eductor/Diffuser type, Eductor/Bliss type, and DRES-Ball type. Normally, Korean naval ships have equipped the Eductor/Diffuser type IRSS composed of eductor, mixing tube, and diffuser. Among the components of Eductor/Diffuser type IRSS, diffuser is the most possible to be detected by threatening weapon systems of enemy.

In this study, the characteristics of design variables for diffuser were investigated. Design variables were set by analyzing the shape of standard model and examined through smaller-the-better
characteristics and Taguchi experiment method [7]. In the performance analysis, a heat flow analysis technique established in previous research [8] was used.

2. Variables and analysis cases for diffuser design

2.1. Design variables

Exhaust gas of high temperature generated in the propulsion engine of naval ships produces turbulent flow as it passes through IRSS eductor and mixes with ambient air at an extent which depends on the size of the mixing tube. The purpose of this research is to identify the characteristics of design variables that affect the performance of diffuser without any changes in eductor and mixing tube.

Design variables were derived by analyzing the shape of standard model of diffuser. Selected design variables of the diffuser are: 1) number of rings (NoR), which is directly connected to the production cost and machinability of the product, 2) tip size (TS) of the ring that forcibly forms an air film on the metal surface of diffuser, 3) diameter (D) of diffuser outlet, which serve to control the gap created by diameter differences between the rings that are related to the internal and external pressure and intake flow, and 4) difference of ring height (DRH), which affects the internal and external pressure difference depending on the correlation between the Bernoulli’s equation and the flow equation.

The shape and dimensions of the standard IRSS model considered in this research are shown in figure 1. These dimensions are from the test model reduced by a factor of 2 from the actual IRSS. Regarding the level of the diffuse design variables, the number of rings was set to 3-5 considering production costs and machinability of the product. The tip size was set to 1-2 times the size of standard model to force the formation of air film. The diameter of diffuser outlet was set to 440-500mm for air suction flow control. The height of rings was set so that it decreases gradually as rings get closer to the diffuser outlet. Here, the difference of ring height was set so that the values of pressure difference with external air would be as uniform as possible.

Figure 1. Standard IRSS model.

2.2. Analysis cases

Total of 81 analysis cases are produced from 4 design variables and 3 levels for each design variable. Since a lot of time is required to handle these all cases, Taguchi experiment method was used to reduce analysis cases without impacts on characteristics of design variables [7]. Using an orthogonal array table $L_9(3^4)$ of the design variables and their levels, the final 9 analysis cases are derived excluding unnecessary analysis cases as shown in table 1.
Table 1. Analysis cases.

| Case | NoR [EA] | TS [m] | D [mm] | DRH [mm] |
|------|----------|--------|--------|----------|
| 1    | 3        | 20     | 440    | 15.00    |
| 2    | 3        | 30     | 470    | 20.00    |
| 3    | 3        | 40     | 500    | 25.00    |
| 4    | 4        | 20     | 470    | 15.00    |
| 5    | 4        | 30     | 500    | 18.25    |
| 6    | 4        | 40     | 440    | 11.25    |
| 7    | 5        | 20     | 500    | 15.00    |
| 8    | 5        | 30     | 440    | 9.00     |
| 9    | 5        | 40     | 470    | 12.00    |

3. Heat flow analysis
In this research, a heat flow analysis technique established through previous research [8] was used, and initial input conditions reflected in the analysis are shown in table 2.

Table 2. Initial condition of heat flow analysis.

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

Figure 2 shows the results of cases 2, 4, and 9, which have different amounts of diffuser rings but same diffuser outlet diameter to verify temperature distribution trends in the metal surface of diffuser.

Figure 2. Temperature distribution of metal surface according to the number of rings.

The temperature of the exhaust gas at the diffuser outlet and the metal surface temperature are summarized for 9 analysis cases as in table 3.
Table 3. Temperature of exhaust gas and metal surface.

| Case | Gas Temp. [°C] | Metal Surface Temp. [°C] |
|------|----------------|--------------------------|
|      | Min. | Max. | Mean | Min. | Max. | Mean |
| 1    | 104  | 444  | 236  | 28   | 126  | 83   |
| 2    | 89   | 431  | 226  | 28   | 100  | 74   |
| 3    | 66   | 451  | 219  | 28   | 75   | 68   |
| 4    | 82   | 417  | 226  | 28   | 88   | 50   |
| 5    | 72   | 433  | 218  | 28   | 80   | 39   |
| 6    | 104  | 445  | 237  | 28   | 115  | 52   |
| 7    | 65   | 451  | 219  | 28   | 77   | 44   |
| 8    | 102  | 434  | 238  | 28   | 106  | 58   |
| 9    | 66   | 449  | 226  | 28   | 93   | 42   |

4. Results analysis

To identify the impact of changes in the sensitivity and level of the diffuser design variables, analysis results were analyzed using the concept of signal to noise (S/N) proposed by Taguchi. In this research, smaller-the-better characteristics shown in equation 1 were used.

\[
S/N = -10 \log \left( \frac{1}{n} \sum (y_i^2) \right)
\]  

(1)

Here, \(n\) is the number of times the analysis was performed, and \(y_i\) is the analysis result.

From the heat flow analysis results, the mean values for exhaust gas temperature and metal surface temperature were converted into S/N ratio using equation (1), and cases in which the factor level of design variables was the same were averaged and indicated in table 4 and 5, respectively. Through table 4 and 5, it can be seen that the design variable that affects the most on the exhaust gas temperature is the diffuser outlet diameter, and the design variable that affects the most on the metal surface temperature is the number of rings.

Table 4. S/N of exhaust gas temperature.

| S/N       | NoR  | TS   | D    | DRH  |
|-----------|------|------|------|------|
| Level 1   | -47.1| -47.1| -47.5| -47.1|
| Level 2   | -47.1| -47.1| -47.1| -47.1|
| Level 3   | -47.1| -47.1| -46.8| -47.1|
| Sum of Squares | 0.00 | 0.00 | 0.74 | 0.00 |
| Contribution Ratio [%] | 0.17 | 0.04 | 99.50 | 0.30 |

Table 5. S/N of metal surface temperature.

| S/N       | NoR  | TS   | D    | DRH  |
|-----------|------|------|------|------|
| Level 1   | -37.5| -35.1| -36.1| -34.3|
| Level 2   | -33.5| -34.9| -34.7| -34.9|
| Level 3   | -33.6| -34.6| -33.8| -35.4|
| Sum of Squares | 31.4 | 0.5  | 7.5  | 1.7  |
| Contribution Ratio [%] | 76.4 | 1.2  | 18.3 | 4.1  |
5. Conclusion

In this research, the main design variables that affect the performance of IRSS diffuser were drawn and its characteristics examined for infrared signature reduction in naval ships. The contents and results of this research are as follows.

1) Design variables were derived for the diffuser, which is the most possible to be detected by threatening weapon systems of enemy, by analyzing the shape of standard model. Selected design variables are number of rings, tip size, diameter of diffuser outlet, and difference of ring height.

2) Analysis cases to examine the design variables were optimized using Taguchi experiment method, and heat flow analyses were performed for the optimized 9 analysis cases.

3) Analysis results were analyzed using the smaller-the-better characteristics of the signal to noise concept. Through this, it was verified that the exhaust gas temperature is greatly affected by changes in the diameter of diffuser outlet, and the metal surface temperature of diffuser is greatly affected by changes in the number of rings of the diffuser.

4) Since this research results are for specific values of exhaust gas flow rate and initial temperature, additional research is required for different conditions. Also, research on the design of mixing tube and eductor connected to the turbulent flow of exhaust gas is required.

6. References

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