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Optimum design of impingement cooling system using differential evolution algorithm in the 2D-Nozzle linear of a turbofan engine

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Abstract

The inlet temperature to the nozzle of the turbine engine is one of the most influential parameters in increasing the thrust. Impingement cooling is one of these methods, which by passing cooler air and then passing through jets, hits the hot wall of the nozzle and causes the heat of the nozzle wall to be absorbed. In this article, the optimization of impingement cooling system has been investigated in three dimensions. The studied geometry is the end walls of the nozzle, which is in the form of a flat plate. This plate includes cooling holes with a circular cross-section. The optimum design is to find the diameter and distances between of the holes. With coupling of software and the code developed with C programming language, different geometries for hole optimization are generated automatically by determining the appropriate constraints and the design is optimized. The optimization is multi-objective and the optimization algorithm is differential evolution. The goal of optimization is to reach a relatively uniform temperature and also temperature lower than the maximum temperature allowed in the nozzle wall. The results of multi-objective optimization are presented as a Pareto front.

Keywords : Turbofan, 2D nozzle, Impingement cooling, Differential evolution algorithm, Optimum design.

1. Introduction

Impingement cooling is one of the most widely used methods in gas turbines. In this method, the cooling fluid impinge the inner surface of the metal at a high speed, as a result, more heat is transferred than flow parallel to the surface.

In cooling, the mass flow rate of cool air is limited. The lower the air temperature, the better the cooling effectiveness. This amount of air is usually taken from the bypass air for the engine, and its temperature and pressure are approximately equal to the fan output values.

Many researches have been done in the field of impingement cooling. The effect of many parameters such as the geometry of the jet holes, the distance of the jet to the wall and the Reynolds numbers of the jet on the target plane have been studied by researchers such as Florschuetz et al. [1,2] and Han and Goldstein [3] and Wiegand and Spring [4].

Spring et al. [5] conducted experimental studies on impingement cooling and found that placing fins between two neighboring jets can provide better heat transfer performance, which depends on the fin geometry on the cooling target wall, and they concluded that the total heat flux can be improved by about 50%.

In some researches, such as Mazaheri et al. [6,7], another method has been used to investigate the heat transfer between two fluid and solid domains, which is called reduce conjugate heat transfer. This method is used to reduce computational time and is especially useful in optimizing internal cooling. In this method, in order to reduce the number of grid and the computational domain, the convection heat transfer coefficient and temperature are taken into account from the experimental results or initial simulation, So external flow is not simulated in the subsequent solutions.

In the mentioned articles, the numerical and experimental investigation of parameters affecting the impingement heat transfer has been done. As a new work in this article, the optimization of the impingement cooling system for the nozzle wall of the turbofan engine is discussed. In this article, by establishing a connection between the commercial CFD software and the code developed with the C programming language, different geometries are automatically generated to optimize the parameters of the holes and their arrangements by determining the appropriate constraints.

2. Methodology

2.1. Objective function

The purpose of optimization is to minimize the temperature gradient on the wall and to reduce the wall temperature to a the value lower than the permissible temperature. Reducing the temperature gradient reduces the thermal stresses and increases the life. The standard deviation (σ) of the temperature represents the temperature changes on the wall, and reducing the value of the standard deviation will reduce the temperature gradient. Therefore, the optimal design of the cooling system will have two objective functions, which are defined as (1).

$$f_1 = \frac{\sigma}{\sigma_{\mathrm{inital}}} \qquad (1)$$

$$f_2 = \frac{max\big((T_{max} - T_{allow}), 0\big)}{max\big((T_{max} - T_{allow}), 0\big)_{inital}}$$

Considering the two-objective nature of the problem, the final design solution is presented as an objective function according to (2), where the coefficients W1 and W2 are the weight of each function, which determines the importance of each one compared to the other. W1 and W2 coefficients are two numbers between zero and one, whose sum is equal to one.

$$F = W_1 f_1 + W_2 f_2 \qquad (2)$$

The optimization process includes three general steps. In the first stage, the geometry is generated according to the number of candidates of the first generation. These geometries are generated according to the constraints set for each of the design variables.

In the second step, the geometry of the cooling holes and the nozzle wall is automatically generated and gridded using the journal file of the Gambit software. The gridded geometry is then imported into the Fluent software. For each geometry mass flow rate is calculated. This step is done for all the candidates of the first generation and the lowest value of the objective function (the best candidate) is determined.

In the third stage, the next generation candidates are produced. These three steps are automatically performed by the optimization code until the convergence of the objective function. For several different values of W1 and W2 coefficients Pareto chart is drawn.

Inline and Staggered arrangements for cooling holes are considered according to Figure 1.

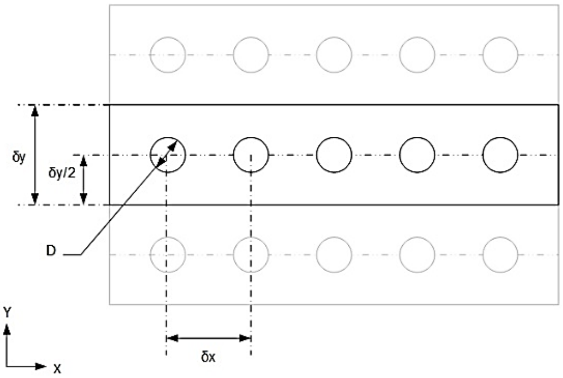
2.2. Constraints

Geometric constraints include the distance between adjacent holes in the x and y directions, which must be greater than D. This distance has been considered in order to prevent extreme temperature gradients and increase the strength of the structure. The range of each variable is shown in Table 1.

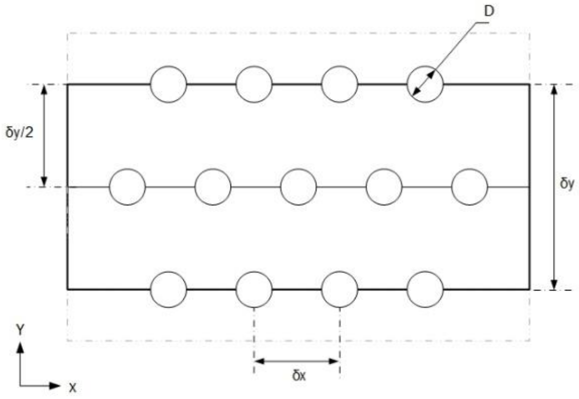
Table 1. Range of design variables

Variable	Range
D	2 – 5 mm
δ_x/D	2 – 5
δ_y/D	2 – 5

Due to the temperature limitation of the wall alloy, the maximum temperature cannot exceed the allowed value. The maximum allowable temperature of the wall is assumed to be 1100 K.



Inline arrangement



Staggered arrangement

Figure 1. Cooling design parameters for Inline and Staggered arrangements

3. Verification

3.1. Optimization algorithm

Before performing the optimal design, it is necessary to ensure the performance of the optimization algorithm. Due to the fact that the global optimal value is not known in real engineering problems, mathematical functions are used. In order to validate the algorithm, Ackley's function has been used. This function has many local minima around its global minimum, which act as an obstacle to finding its global optimum point. The general form of this function is (3).

$$f(x) = -20\exp\left(-0.2\sqrt{\frac{1}{j}\sum_{i=1}^{j} x_i^2}\right) - \exp\left(\frac{1}{j}\sum_{i=1}^{j}\cos(2\pi x_i)\right) + 20 + \exp(1) \qquad (3)$$

This function has a global minimum equal to zero at $\mathrm{x_i} = 0$. The number of variables (j) is equal to 5 and the number of members of each generation is 10.

3.2. CFD solver

To validate the flow and heat transfer solver, simulation using geometry and experimental test conditions have been performed by Xing et al. [8]. They have used impingement cooling holes with an inline arrangement. In order to validate the numerical solution, the Nusselt number on the surface of the cooling wall and the center of the holes has been compared with the experimental values.

4. Results and Discussion

The Pareto diagram for different values of the weight coefficient W1 between zero and one is shown in Figure 2 and Figure 3. As previously stated, each point on the Pareto diagram is superior to other points in one criterion (an objective function), so choosing the optimal point depends on the type of design, the tolerance level of thermal stresses, and other design criteria. For the geometry with Inline arrangement, the temperature standard deviation values for W1=0 and W1=1 are equal to 28.43 and 17.6, respectively, which means that the standard deviation from W1=0 to W1=1 has decreased by about 60%. The maximum temperature also increases around 120 K. For geometry with staggered arrangement, the temperature standard deviation values for W1=0 and W1=1 are 24.98 and 14.63, respectively, which means that the standard deviation from W1=0 to W1=1 has decreased by about 70%. The maximum temperature also increases around 125 K.

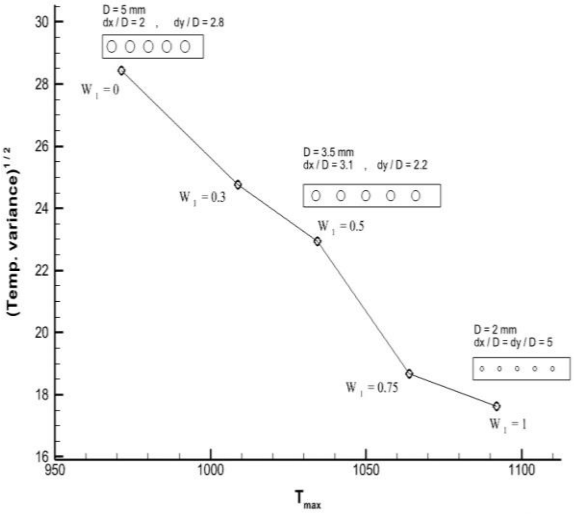


Figure 2. Pareto front for different values of w1 in Inline arrangement

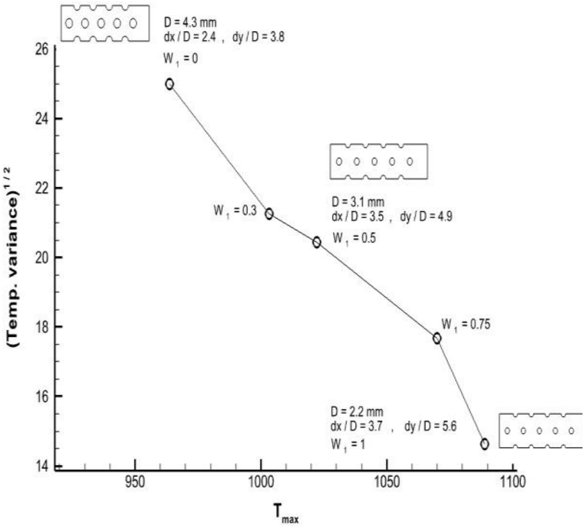


Figure 3. Pareto front for different values of w1 in Staggered arrangement

According to Figure 1, it should be noted that the number of holes in the elements is constant, but the diameter, length and width of the element are not constant. Therefore, if the area of the nozzle wall is equal to $A(m^2)$, in each of the optimal geometries in Figure 2 and Figure 3, the number of holes in the nozzle wall will also be different for different values of w1.

In addition, the optimization objective or the objective function is the factor determining the distances and diameters of the holes. Therefore, we cannot generally expect an increase in the number of holes and a decrease in distances. It should be noted that in the optimization of engineering problems and this research, global optimization is not claimed, and it is only claimed that an optimal geometry has been obtained compared to the initial geometry.

5. Conclusions

In this article, the optimization of the nozzle wall of a turbine engine was done. The results of the optimization of the cooling holes are expressed as follows:

- Minimizing the temperature gradient in the wall, in addition to reducing thermal stresses, will minimize the air mass flow required for cooling.
- Minimizing the air required for cooling only reduces the diameter of the holes and slightly reduces the temperature changes on the wall because the position of the holes relative to each other plays a greater role in temperature uniformity.
- In all the optimized geometries, the maximum temperature is near the first hole, and the temperature gradually decreases by moving in the flow direction.
- Increasing the cross-sectional area of the cooling holes increases the convection heat transfer and the amount of air required for cooling. Increasing the heat

transfer in certain points of the wall will increase the temperature changes in the wall and reduce the life of the wall, and using more cooling air reduces the efficiency of the cooling system.

- For staggered hole arrangement compared to Inline, the temperature uniformity on the wall is higher (the temperature standard deviation value is lower).

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