NUMERICAL INVESTIGATION OF THE EFFECT OF WALL TEMPERATURE ON THERMAL ENVIRONMENT OF TWO-DIMENSIONAL TRANSVERSE GAP

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Abstract

By solving the compressible Navier-Stokes equations, a CFD software is developed independently, which can well simulate the flow in the gap in hypersonic vehicle surface. An analytical study has been performed through this software to investigate the wall temperature effects on thermal environment of two-dimensional transverse gap, and the mechanism of the influence is also analyzed. The research indicates that the influence of wall temperature change on thermal environment mainly comes from two aspects： one is to change the wall temperature gradient directly, the other is to change the physical parameters near the wall, and then change the whole flow structure. The joint action of the two aspects determine the variation law of the heat flux distribution. For the gap flow, the local high heat flux regions are mainly caused by the reattachment flow. On the one hand, increasing the wall temperature will reduce the wall temperature gradient, which will lead to the decrease of the heat flux; on the other hand, it will increase the viscosity coefficient near the wall, thicken the boundary layer, enhance the viscous dissipation, restrain the separation and reattachment flow at the entrance of the gap and the vortexes flow in the gap, which will greatly reduce the corresponding heat flux peak value. The hot wall correction formula widely used in engineering application ignores the influence of wall temperature on the flow structure. So the local heat protection design using the hot wall correction formula will produce a large deviation.

Keywords: hypersonic; gap; numerical simulation; wall temperature; heat-flux distribution

1. General Introduction

Because of its great military and economic value, hypersonic vehicle has become another military commanding height in the "post nuclear weapon era"[1-3]. Whether it is a reentry hypersonic vehicle or a cruise hypersonic vehicle, how to overcome the serious aerodynamic heating problem is one of the key technologies to be solved. In this regard, different hypersonic vehicles will adopt different thermal protection systems due to their different thermal protection requirements, and the thermal tile thermal protection system is one of the common ones, such as the thermal protection system of ceramic thermal tile adopted by the US space shuttle[4]. In order to accommodate the structural warpage caused by load and thermal expansion, there must be certain gaps between the thermal tiles[5].

Due to the existence of the gap, the flow characteristics and heat transfer mode of the aircraft surface will change greatly. For example, the separation and reattachment of the boundary layer will occur at the entrance of the gap; The gap interference will increase the turbulence and accelerate the boundary layer transition; The vortical structure will be rolled up in the gap and a large amount of heat will be drawn into the gap; Due to the narrow gap, the radiation effect will be blocked, and so on. All of the above may cause the local heat flux to increase, which will cause serious ablation of the thermal protection system due to local overheating, thus affecting the thermal performance of the aircraft and even the whole flight safety. Therefore, it is very important to accurately predict the thermal environment of gaps and obtain the influence of different factors on the thermal environment of gaps.

At present, a lot of research have been made on the aerodynamic heating of the thermal tile gap. A large number of aerodynamic heating experiments have been carried out in the United States for the space shuttle thermal tile thermal protection system gap too. The influence of the inflow parameters, the geometry parameters of the gap, the arrangement of the gaps on the flow characteristics and the heat flux distribution are studied[6-8]. NASA has conducted a series of flight tests on the gap heating measurement of thermal protection tile of space shuttle in the 1980s[9]. Many domestic scholars have also carried out experimental research on the thermal environment of the thermal tile gap[10-14]. Generally, the research on these gaps at home and abroad mainly presents three characteristics. First, most of the research focus on the thermal environment, and the research on the vortex structure in the gap is relatively few, but the vortex structure in the gap has a great influence on the heat flux on the wall of the gap[14]. Secondly, most of the research adopts wind tunnel experiment, and a few utilize CFD. This is mainly due to the complexity of the gap flow, the huge difference between the gap size and the aircraft size, and the huge difference between the inside gap flow characteristics and outside, which makes the numerical simulation difficult. Thirdly, the wall temperature is mainly set as 300K uniform "cold wall", which ignore the influence of the wall temperature, but the wall temperature has a great influence on the gap flow.
By solving the compressible Navier-Stokes equations, our research group independently developed a set of CFD software which can better simulate the flow characteristics in the gap. The results obtained by this software have relative high reliability[14]. On this basis, this paper uses the software to simulate the transverse thermal tile gap, focusing on the influence of wall temperature on the vortical structures and heat flux in the gap, and obtain some meaningful conclusions.

2. Introduction of numerical method

The numerical simulation method used in this paper is the finite volume method, in which the calculation of inviscid flux is based on van Leer flux splitting method[9], and the enthalpy conservation correction is carried out[15]. The corresponding interface interpolation is based on the muscl (Monotonic Upstream-Centered scheme for Conservation Laws) method with Van Albada limiter [16,17], and the viscous flux is based on the second-order central scheme. The implicit LU-SGS (Low Upper Symmetric Gauss-Seidel) method is used to advance the time[18]. The viscosity coefficient in the calculation is given by Sutherland formula, Prandtl number is Pr=0.72, specific heat ratio is constant 1.4, and full laminar flow calculation is adopted.

The verification of this method has been carried out in reference [14], and the verification results are shown in Figure 1. A series of wall heat flux is obtained by continuously densifying the grid in the gap (group A is the thinnest, group E is the densest). When the gap is densified to a certain extent (Group C, D, E), the wall heat flux converges and is in good agreement with the experimental results, which shows that the method in this paper has high reliability in calculating the flow in the gap.

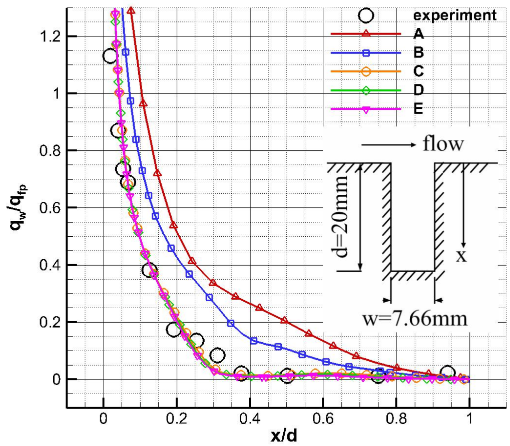

Figure 1 – Comparison of gap heat-flux distribution with experimental

3. Calculation model, condition and grid

3.1 Calculation Model

A calculation model of two-dimensional transverse gap (infinite length plate gap) is designed based on the experimental models of thermal tile wind tunnel testes in reference [19-20]. The calculation model is a two-dimensional wedge-shaped plate (infinite plate) with a length of 884mm, a height of 40mm and a head radius of 2mm, and a two-dimensional gap (infinite gap) with a width of 4mm, a depth of 25mm and entrance rounding radius of 0.5mm is set on the plate 580mm away from the head. The cross-section diagram of the calculation model is shown in Figure 2.

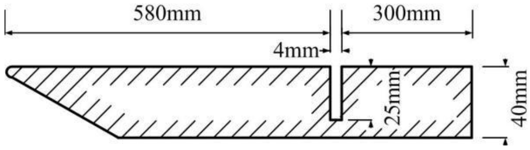

Figure 2 – Sketch of experimental model

3.2 Calculation Condition

Reference to the trajectory parameters of hypersonic space flight test in reference [21], the calculation inflow conditions are as follows: 30 km, Mach number 10, angle of attack 20 °. Seven uniform wall temperatures of 300K, 500K, 700K, 900K, 1100K, 1300K and 1500K are taken for numerical simulation.

3.3 Calculation Grid

In order to ensure the uniformity of grid distribution, and avoid over dense grid in space (the entrance of the gap), this paper designs the grid topology at the entrance of the gap, as shown in Figure 3. The mesh size of the first layer off the wall is calculated by the inflow Reynolds number. The mesh Reynolds number is always kept below 8, and the mesh density meets the requirement of mesh independence in Figure 1.

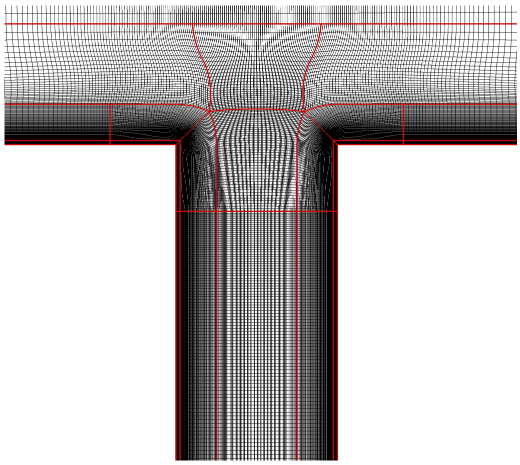

Figure 3 – Topological structure of grid

4. Result analysis

4.1 Effect of Wall Temperature on Flow Structure in Gap

For two-dimensional transverse gap flow, a vortical structure will be formed inside the gap. Downward the gap, the vortical structure will gradually disappear due to viscous dissipation. In some cases, a "dead water zone" will even be formed at the bottom of the gap[22]. In order to observe the effect of wall temperature on the flow structure of the gap, the space streamline diagrams of the gap under different wall temperatures are made, as shown in Figure 4. It can be seen from the figure that six main vortexes are formed in the gap at 300K wall temperature, and the first four main vortexes are relatively full (the fullness here means that the main vortexes are close to the circle from the streamline, and the center of vortex rotation is close to the geometric center of vortex). With the increase of the wall temperature, the viscous coefficient and the viscous dissipation increase. With the increase of wall temperature, the vortical structure in the gap becomes less and less full. At 300K, the vortical structure start to become less full from the fifth main vortex, at 500K, the vortical structure start from the fourth main vortex, at 700K, the vortical structure start from the third main vortex, and at 1100K, the vortical structure start from the second main vortex.

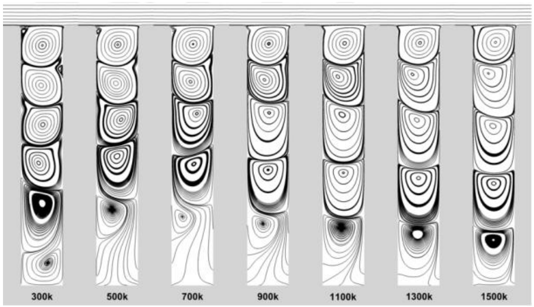

Figure 4 – Streamline diagram of gap space

The fullness degree of vortical structure is related to the rotation speed of vortical structure to a certain extent. In order to more directly observe the influence of wall temperature on the flow structure of the gap, the cloud images of the flow field speed inside the gap are made, as shown in Figure 5. It can be seen from the figure that with the increase of wall temperature, the rotation speed of the vortical structure decreases significantly, and the "low speed" flow area with flow speed less than 2m/s (blue area) at the bottom of the gap expands to the entrance of the gap. As mentioned earlier, this is mainly due to the increase of dissipation, which makes the energy of vortical structure in the gap dissipated quickly, the velocity decreases and the flow tends to be stationary.

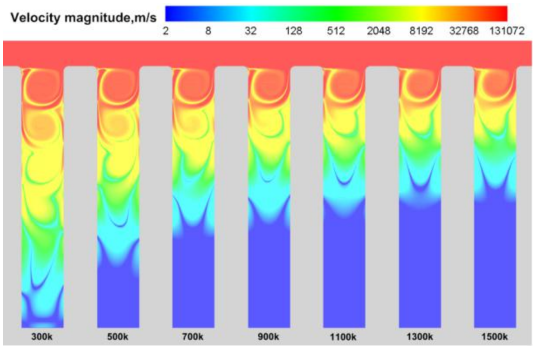

Figure 5 – Velocity magnitude distribution of gap space

For the separated reattachment flow at the entrance of the gap, the wall temperature increases, the viscosity coefficient increases, the boundary layer thickens and the separated reattachment flow is restrained. Figure 6 shows the local streamline and the location of separation point at the leading edge of the gap entrance (near the direction of inflow) under different wall temperatures. It can be seen from the figure that at 300K, affected by the first main vortex, an obvious secondary vortex will be formed near the main flow separation point. With the increase of temperature, the size of the secondary vortex decreases and disappears at 1100K. At the same time, the position of the separation point of the main flow at the front edge of the gap entrance moves backward with the increase of the wall temperature (as shown in the lower right corner of Figure 6), and the position of the reattachment point of the main flow at the rear edge of the gap also moves backward. The above two phenomena are caused by the inhibition of separated reattachment flow with the increase of wall temperature.

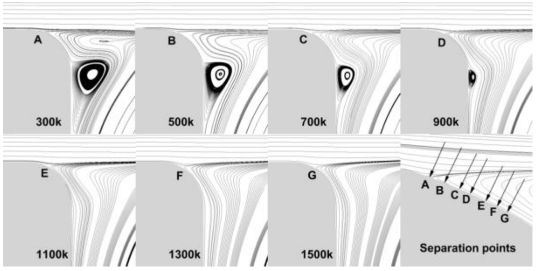

Figure 6 – Spatial streamline diagram of the gap leading edge

4.2 Effect of Wall Temperature on Heat Flux of Gap Wall

It is generally believed that if the same inflow heats a higher temperature object, the heat entering the interior of the object is naturally lower. The above cognition is based on the basic conclusion that the increase of wall temperature will directly reduce the wall temperature gradient, and then reduce the wall heat flux. The actual situation is that the change of wall temperature will change the whole flow structure (as described in Section 3.1), and then lead to further change of heat flux. For the plate gap model in this paper, there are mainly two high heat flux regions in the gap area, one is the first main vortex reattached on the front wall of the gap, the other is the main stream reattached on the rear edge of the gap entrance, and the latter has higher heat flux.

Taking the entrance of the front wall of the gap as the zero point and the distance S around the bottom of the gap as the abscissa, the change of heat flux with S is shown in Figure 7 (in order to avoid confusion, only part of the heat flux results under the wall temperature are shown in the figure, and the high heat flux area formed by the first main vortex on the front wall of the gap is magnified). It can be seen from Figure 7 that the high heat flux formed by the first main vortex decreases greatly with the increase of wall temperature. From the orange heat flux curve at 300K, it can even be seen that the secondary vortex forms a high heat flux at the entrance of the gap. This change is due to the joint action of the increase of wall temperature directly reducing the wall temperature gradient and changing the flow structure (reducing the rotation intensity of vortical structure). The dimensionless heat flux distribution, non-dimensionalized by the stagnation point heat flux at the leading edge of the plate, is shown in Figure 8. Non-dimensionalizing can filter out the influence of the decrease of wall temperature gradient on the wall heat flux to a certain extent, and the variation law of dimensionless heat flux can basically reflect the influence law of the change of flow structure on the wall heat flux. As mentioned in Section 3.1, with the increase of wall temperature, the viscosity coefficient increases, and the viscous dissipation inside the gap increases, thus reducing the rotational strength of the vortical structure. Because the high heat flux region on the front wall of the gap is caused by the reattachment of the first main vortex on the front wall, the decrease of vortex rotation intensity will reduce the high heat flux. It can be seen from figure 8 that the decrease of heat flux caused by the decrease of vortex rotation intensity (the change of flow structure) is very obvious, and even dominates in the two factors.

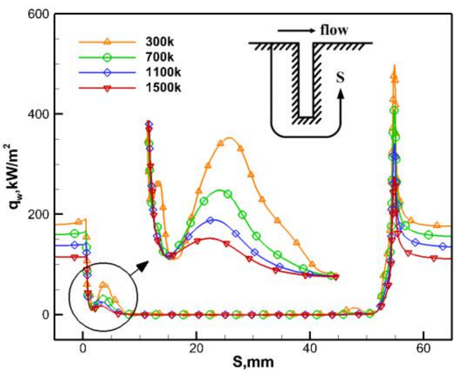

Figure 7 – Heat flux distribution of the gap at different wall temperatures
(front wall magnified, dimensional)

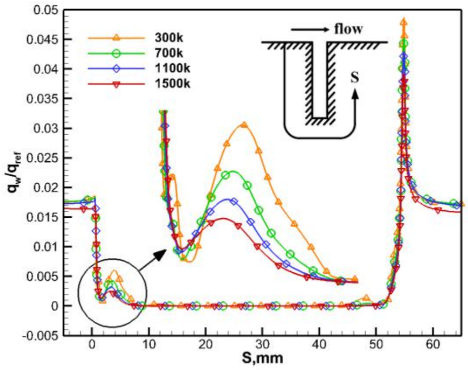

Figure 8 – Heat flux distribution of the gap at different wall temperatures
(front wall magnified, non-dimensional)

In most cases, the high heat flux at the rear edge of the gap entrance is the peak heat flux of the whole gap structure, which is one of the areas that need special attention in the thermal protection design of the gap structure. The high heat flux in this region is formed by the mainstream outside the gap reattaching at the rear edge of the gap entrance. The variation of heat flux with wall temperature is basically the same as that of the peak value of heat flux with wall temperature in front of the gap, but it changes in quantity. Figure 9 shows the heat flux distribution of the rear edge of the gap at different wall temperatures, and figure 10 shows the distribution of the dimensionless heat flux which is dimensionless by the stagnation point heat flux peak of the plate. It can be seen from the figure that whether the dimension heat flux or the dimensionless heat flux decreases with the increase of wall temperature. The reason is as described in Section 3.1. In addition to directly changing the wall temperature gradient, the increase of wall temperature also inhibits the intensity of separation and reattachment to a certain extent.

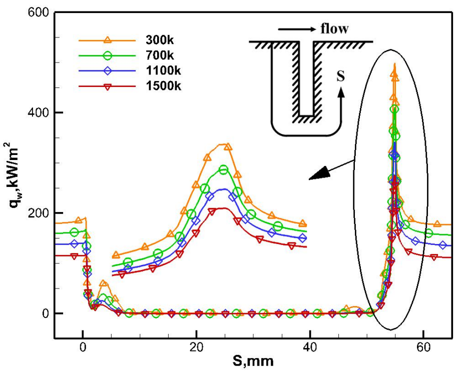

Figure 9 – Heat flux distribution of the gap at different wall temperatures
(back edge magnified, dimensional)

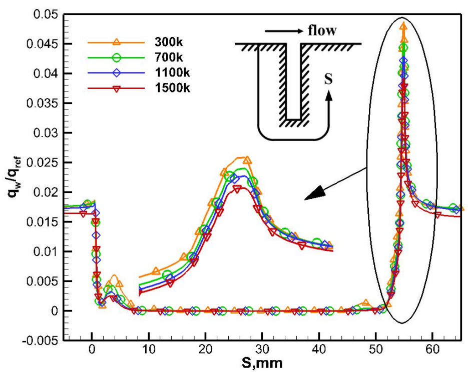

Figure 10 – Heat flux distribution of the gap at different wall temperatures

(back edge magnified, non-dimensional)

In order to study the specific variation of heat flux peak value with temperature, table 1 lists the heat flux peak value of each high heat flux region under different wall temperature and its corresponding dimensionless value. Among them, SPD (Stabilization Point Dimensional) group is the dimensional heat flux value of stagnation point at the leading edge of the plate, FWD (Front Wall Dimensional) group is the dimensional heat flux peak value at the front wall of the gap, FWN (Front Wall Non-dimensional) group is the dimensionless heat flux peak value corresponding to FWD group, and BED (Back Edge Dimensional) group is the dimensional heat flux peak value at the rear edge of the gap entrance, BEN (Back Edge Non-dimensional) group is the corresponding dimensionless heat flux peak of BED group. It is not difficult to see from the FWN and BEN groups that the effect of wall temperature increase on the flow structure and the heat flux change is very significant, especially on the heat flux peak value of the front wall (FWN group).

Table 1 Heat flux peak value of the high heat flux region of gap（dimensional:kW/m^2）

T_w	300K	500K	700K	900K	1100K	1300K	1500K
SPD	10238	9525	9051	8454	7956	7544	7014
FWD	62.11	48.82	38.87	31.29	25.63	21.27	17.51
FWN	0.331	0.276	0.237	0.207	0.183	0.165	0.152
BED	498	452	410	373	341	310	275
BEN	0.048	0.047	0.045	0.044	0.042	0.041	0.039

4.3 Adaptability of hot wall correction formula

In practical engineering, because the wall temperature cannot be predicted in advance, the wall temperature will be usually set as 300K (room temperature) no matter in numerical simulation or wind tunnel test during the thermal environment assessment. Then, the heat flux is modified to the heat flux at high wall temperature according to the formula proposed by Chen[23-24]. The formula for the correction of the thermal wall is as follows:

$$q_h = q_c \cdot \frac{h_{re} - h_h}{h_{re} - h_c} \tag{1}$$

In the above formula, q_h is the low wall temperature heat flux, q_c is the high wall temperature heat flux, h_{re} is the boundary layer recovery enthalpy, h_c is the low wall temperature enthalpy, h_h is the high wall temperature enthalpy. Formula (1) can be simply derived from the heat transfer heat flux calculation formula. The heat transfer heat flux calculation formula is as follows:

$$q = C_H \left(h_{re} - h\right) \tag{2}$$

In the above formula, C_H is the convective heat transfer coefficient. According to formula (2), formula (1) ignores the difference of convective heat transfer coefficient under different wall temperature. In practical application, the enthalpy value is difficult to obtain directly and is usually replaced by temperature, so equation (1) can be changed as follows:

$$q_h = q_c \cdot \frac{T_{re} - T_h}{T_{re} - T_c} \tag{3}$$

In the above formula, T_{re} is the boundary layer recovery temperature, T_c is the low wall temperature, T_h is the high wall temperature, in this equation, the recovery temperature is still difficult to obtain directly, so using the relationship between the recovery temperature and the total temperature of the inflow, the formula (3) is further written as:

$$q_h = q_c \cdot \frac{r \cdot T_o - T_h}{r \cdot T_o - T_c} \tag{4}$$

In the above formula, T_o is the total temperature of the inflow and r is the coefficient of restitution, which is usually 0.89 in the case of laminar flow and 0.92 in the case of turbulence. It can be seen from formula (4) that the hot wall correction formula has a good correction effect on the temperature gradient change caused by the change of wall temperature, but it cannot correct the heat flux change caused by the change of flow structure. This conclusion will be verified in combination with the specific numerical simulation results.

The heat flux peak values of three high heat flux zones, i.e. the stagnation point at the leading edge of the plate, the front wall surface of the gap and the rear edge of the entrance of the gap, are corrected to the heat flux at the wall temperature of 1500K. The comparison results are shown in Figure 11, and the corresponding correction deviation (the ratio of the absolute deviation between the correction value and the 1500K value and the value of 1500K) is calculated as shown in Table 2. In Table 2, SPC (Stagnation Point Correction) represents the heat flux at the leading edge of the plate corrected to 1500K wall temperature, and the SPE (Stagnation Point Error) represents the stagnation point heat flux correction deviation; FWC (Front Wall Correction) represents the heat flux at the front wall of the gap corrected to 1500K, FWE (Front Wall Error) represents the correction deviation of the front wall; BEC (Back Edge Correction) represents the heat flux at the back edge of the gap entrance corrected to 1500K, and BEE (Back Edge Error) represents the corresponding correction deviation.

It can be seen from Figure 11 and table 2 that the modified formula is very suitable for the stagnation point of the head, the corrected heat flux values of different wall temperatures are basically the same, and the maximum deviation is 1.4%. The results show that the modified formula is not suitable for the front wall of the gap, the heat flux value corrected from 300K to 1500K is 146% higher than that calculated directly from 1500K. The applicability of the modified formula for the trailing edge of the gap entrance is between the two, the heat flux value corrected from 300K to 1500K is 25% larger than that calculated directly from 1500K. The flow structure of stagnation point in the head is simple, and the change of wall temperature has little effect on this flow structure, but only makes the wall temperature gradient change, so formula (4) can correct the heat flux well. It can be seen from section 3.2 that the wall temperature change will affect the vortical structure to a great extent, so formula (4) will produce a large deviation in correcting the heat flux on the wall in front of the gap; In the same way, the change of wall temperature will affect the separation and reattachment flow of the main flow at the entrance of the gap to a certain extent, so the applicability of formula (4) for the trailing edge of the entrance of the gap is between the two. Therefore, the conclusion that formula (4) cannot correct the change of heat flux caused by the change of flow structure has been verified to a certain extent.

It is worth mentioning that, for gap flow, the corrected heat flux from 300K to high wall temperature by the hot wall correction formula is often too large, which will add some invalid margin in the thermal protection design, which is not conducive to the fine design of aircraft thermal protection system.

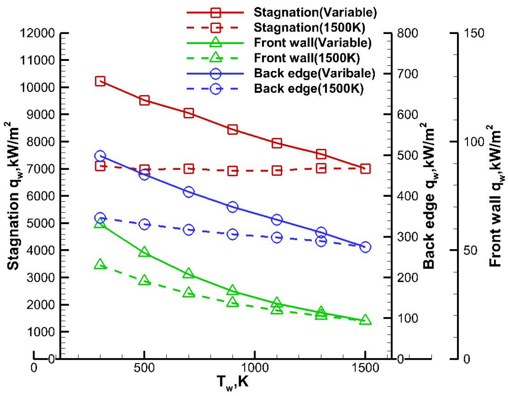

Figure 11 – Comparison of the heat flux peak value correction results

Table 2 Comparison of the heat flux peak value correction results and the errors

T_w	300K	500K	700K	900K	1100K	1300K	1500K
SPC	7114	6974	7002	6933	6941	7030	7014
SPE	1.4%	0.5%	0.2%	1.1%	1.0%	0.2%	0.0%
FWC	43.16	35.74	30.07	25.66	22.36	19.82	17.51
FWE	146%	104%	71%	46%	27%	13%	0%
BEC	346	331	317	306	298	289	275
BEE	25%	20%	15%	11%	8%	5%	0%

5. Conclusion

In this paper, a CFD software which can simulate the gap flow well is developed. The influence of wall temperature on the thermal environment of the gap is studied by using the software. The influence mechanism is analyzed, and the applicability of the formula is discussed briefly. The conclusions are as follows:

- The increase of wall temperature will increase the viscosity coefficient and the thickness of boundary layer, which will restrain the separation and reattachment of the mainstream at the entrance of the gap to a certain extent. In addition, the increase of viscosity coefficient will increase the viscous dissipation effect inside the gap, and then weaken the flow intensity of vortical structure;
- On the one hand, the increase of wall temperature will directly reduce the wall temperature gradient then reduce the heat flux; on the other hand, it will change the flow structure to affect the wall heat flux. For the gap flow, the latter has a very significant effect.
- The traditional hot wall correction formula has good applicability for stagnation point and large area without interference, but it can't correct the heat flux change caused by the change of flow structure, so it has poor applicability for gap flow, and the modified high wall temperature heat flux will be larger than the real value.

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7. Copyright Statement

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