Forced Convection Heat Transfer for Stratospheric Airship Involved Flight State

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Abstract: Forced convection heat transfer is a significant factor for the thermal control of a stratospheric airship. However, most of the researches were conducted without considering the influence of flight state causing serious errors. In order to accurately predict the forced convection heat transfer of the stratospheric airship at an angle of attack, firstly, an empirical correlation of Nusselt number \((Nu)\) as function of Reynolds number \((Re)\) and length to diameter ratio \((e)\) is developed under horizontal state based on a validated computational fluid dynamic (CFD) method. Then, a correction factor \(K\), considering its angle of attack \((\alpha)\), is proposed to modify this correlation. The results show that: (1) Nusselt number increases with the increase of Reynolds number, decreases as the length to diameter ratio changes from 2 ~ 6, and increases as the angle of attack changes from 0° ~ 20°. (2) At higher Reynolds number, the calculated results are 30 percent higher than those of previous studies with \(\alpha = 20°\). (3) Compared with \(\alpha\) and \(e\), the effect of \(Re\) on correction factor \(K\) can be ignored, and \(K\) is a strong equation of \(\alpha\) and \(e\). The efficiency of heat transfer is increased by 6 percent with \(\alpha = 20°\). The findings of this paper provide a technical reference for the thermal control of a stratospheric airship.

Keywords: stratospheric airship; angle of attack; forced convection heat transfer; flight state; thermal control

1. Introduction

A stratospheric airship is a type of aircraft that takes off by buoyancy. Compared with other aerostats, the stratospheric airship has its unique advantages and is widely used in civil fields such as satellite communications, meteorological measurements, and military fields such as surveillance and defense [1–3].

Convection heat transfer process, including natural convection and forced convection, is one of the most common natural phenomena, which is widely used in almost all of the engineering fields, such as heat exchanger [4,5], aircraft [6–9], electronics [10], airship [11–22], and so on.

Thermal performance is one of the most important factors affecting the flight state of a stratospheric airship. The stratospheric airship is filled with a large amount of gas, and it experiences a rough external environment during flight, as the change in temperature affects the buoyancy to a large extent [23]. In the past decades, many research activities have been held on the forced convection heat transfer of a stratospheric airship. In their researches, Kreith and Kreider [11] established a simple numerical model to simulate the average temperature of balloon envelope and lifting gas. Yao [12] proposed a multi-node thermal transient model of stratospheric airship and verified the model using high-altitude flight experiments. Fang [15] built a two-node thermal model to analyze heat
source and heat transfer patterns that affect thermal balance and thermal performance of airships flying in stratospheric environment. However, the most existing forced convection heat transfer correlations are only applicable in the case of low Reynolds number, so Dai [17] investigated the steady forced convection heat transfer of an isothermal spherical aerostat with the Reynolds number range from 20 to $10^8$, and a new piecewise correlation was proposed. Later, Shi [21,22] proposed a new fixed-point adjustment method of an airship to solve the problem of height instability due to dramatic daily-temperature swings. The airship membrane was discretized into a triangular element to enhance the computing accuracy, and a multi-node thermodynamic model of the airship was established.

In summary, despite the attainment of considerable knowledge on the forced convection heat transfer of a stratospheric airship (through experimental or numerical work), the most relevant empirical correlations are only applicable to spherical airships or airships flying under horizontal state. So many conclusions are not universal because the consistency of study object and correlation equations geometric model is often neglected. And, no specific correlation is available on the external forced convection heat transfer of an ellipsoidal airship flying with a certain angle of attack, although the literature has pointed out that the efficiency of heat transfer is increased by 7 percent considering the angle of attack [24]. The heat transfer criterion equations need to be improved. The present study investigates the effects of Reynolds number, length to diameter ratio, and angle of attack on the thermal characteristics of an ellipsoidal airship to answer this demand. A new correlation of the average Nusselt number is built based on the data obtained from computational fluid dynamic (CFD) calculations. Moreover, a correction factor $K$ considering angle of attack is proposed to modify this formula.

2. Numerical Method

2.1. Geometric Model

An ellipsoidal airship is taken as the research object in this paper, and its generatrix equation [25] can be written as

$$\frac{x^2}{(L/2)^2} + \frac{y^2}{(D/2)^2} = 1 \quad (L > D > 0) \quad (1)$$

where $L$ is the length of the airship, $D$ is the diameter of the airship.

In recent years, the CFD method has been able to successfully simulate the thermal characteristics of an airship, owing to the rapid development of computer technology. Moreover, its precision is sufficient to meet the demands of engineering calculation. However, the scaled-model is only geometrically similar to the actual object, and the Reynolds number is not equal, which lead to a large error due to the scale effect when converting the model data into the actual object [26,27]. Thus, a full-scale airship model with $L = 100$ m is used in this paper to accurately simulate the forced convection heat transfer over the external surface of an airship. Here, the length to diameter ratio is defined as $\varepsilon = L/D$. Five cases with $\varepsilon = 2, 2.5, 3, 4,$ and $6$ are numerically simulated by changing the value of $D$ to change the value of $\varepsilon$. The values of $L$ and $D$ are shown in Table 1.

| $L = 100$(m) | $E = L/D$ | 2 | 2.5 | 3 | 4 | 6 |
|--------------|-----------|---|-----|---|---|---|
| $D$(m)       |           | 50| 40  | 33.33 | 25 | 16.67 |

The numerical simulations are based on the CFD software, Version 18.0, and the ICEM software, Version 18.0 is used for the meshing. The research object in this paper is a symmetrical structure without a tail wing; thus, only a 1/2 body structure is used. At the same time, in order to ensure the symmetry of the flow field structure, a “Symmetry” boundary condition is used, and the airflow direction is parallel with the SYM (as shown in Figure 1).
2.2. Control Equations

The phenomena of flow and heat transfer were controlled by the following equations [28]:

Continuity equation

$$\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} + \frac{\partial V_z}{\partial z} = 0$$  (2)

Momentum equation

$$\rho \left( V_x \frac{\partial V_i}{\partial x} + V_y \frac{\partial V_i}{\partial y} + V_z \frac{\partial V_i}{\partial z} \right) = -\frac{\partial P}{\partial i} + \rho g_i + \mu \left( \frac{\partial^2 V_i}{\partial x^2} + \frac{\partial^2 V_i}{\partial y^2} + \frac{\partial^2 V_i}{\partial z^2} \right)$$  (3)

where $i$ represents x-component, y-component, and z-component, $V$ is the velocity vector, $\mu$ is the viscosity of the fluid, $P$ is the pressure of the fluid, $\rho$ is the density of the fluid, $g$ is the gravitational acceleration.

Energy equation

$$\rho c_p \left( V_x \frac{\partial T}{\partial x} + V_y \frac{\partial T}{\partial y} + V_z \frac{\partial T}{\partial z} \right) = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)$$  (4)

where $c_p$ is the specific heat of the fluid, $k$ is the thermal conductivity and $T$ is the temperature of the fluid.

2.3. Computational Domains, Mesh, and Boundary Condition

The computational domain and the configuration of the airship are illustrated in Figure 1. Figure 1 shows that the boundary conditions of the computational domain are divided into INLET, OUTLET, WALL, FARWALL, and SYM. The INLET boundary is assumed to be a uniform velocity inlet given the magnitude and direction. Different angles of attack are indicated by changing the direction of the velocity. The OUTLET boundary is assumed to be “Opening” with a reference pressure of 0 Pa. The FARWALL boundary is assumed to be “Opening”. The WALL boundary is assumed to be a no-slip wall, and its temperature is 298.15 K. The SYM boundary is assumed to be “Symmetry”. The thermal physical properties of the flow fluid are assumed to be constant at a temperature of 288.15 K, and the pressure of the computational domain is set as 1 atm. The fully implicitly coupled multigrid linear solver is used. The high resolution scheme is used for advection and turbulence numerics.

Given the large physical size of an airship, its Reynolds number may easily increase to a magnitude over $10^6$, which is far beyond the critical Reynolds number. Thus, the flow around an airship is a typical turbulent flow. The computational domain is divided into two separate subdomains, namely, the internal domain and the external domain, to precisely investigate the thermal characteristics over...
the external surface of an airship. The mesh of the internal domain, including boundary layers, is fine, and the first layer of the mesh around the surface lies at $y^+ \leq 1$. The mesh of the external domain is relatively coarse. Through convergence analysis, the number of elements is controlled at about 2,000,000. The max aspect ratio is 36.4, the min quality is 0.549, the max value of max angle is 147, and the min value of min angle is 34.2, and the min equiangle skewness is 0.37. The computational mesh is illustrated in Figure 2.

![Computational Mesh](image)

**Figure 2.** (a) Sketch map of the external domain mesh; (b) Sketch map of the internal domain mesh.

2.4. Turbulence Model

The turbulence model has a significant effect on the results of the numerical simulation [29]. The suitability of the $k$-$\omega$ turbulence model in a study on forced convection heat transfer around an ellipsoidal airship has been proven in the literature [30]. To further verify the applicability of the turbulence model in the present study, a numerical simulation is carried out by using $k$-$\omega$ turbulence model, and the pressure coefficients $C_p$ is plotted in Figure 3. Because experimental results are not available to directly verify the numerical results of an ellipsoidal airship, the pressure coefficients data of a spherical airship is used as a reference to verify the turbulence model and numerical scheme. The size of the model and boundary conditions are same with the literature [31]. The pressure coefficients obtained in the present study are compared with the experimental measurements of Achenbach. In Figure 3, it can be observed that the performance computed with $k$-$\omega$ turbulence model is close to the experimental measurements. Considering the smaller discrepancy, thus, $k$-$\omega$ turbulence model is used in the present study.

![Pressure Coefficients Comparison](image)

**Figure 3.** Comparison of pressure coefficients between literature and the present study.
3. Results and Discussions

Existing studies have shown that the main factors affecting forced convection heat transfer around an ellipsoidal airship are the length to diameter ratio and the Reynolds number under a horizontal state [20,28,32–34]. However, an airship generally ascends or descends at a certain angle of attack; thus, estimating its thermal characteristics under this condition is necessary.

The effects of different parameters on forced convection heat transfer are studied in this paper. The values of a single parameter is numbered from 1 to 5, as shown in Table 2.

Table 2. Values of different parameters.

| Parameters | Values |
|------------|--------|
| \( Re \times 10^6 \) | 1, 2, 3, 4, 5 |
| \( e \) | 0, 5, 10, 15, 20 |
| \( \alpha/(°) \) | 0, 5, 10, 15, 20 |

A reference value is set with \( Re \) of 1 \( \times 10^7 \), \( e \) of 2, and \( \alpha \) of 0°. Only the value of the analyzed parameter is changed during the analysis, and the values of the remaining two parameters are the same as the reference values. A total of 15 cases is conducted in this part to study the effects of different parameters on the forced convection heat transfer around an ellipsoidal airship.

3.1. Effects of Different Parameters on Heat Transfer

Figure 4 shows the relation between the average Nusselt number (\( Nu \)) and \( Re \), \( e \), \( \alpha \). \( Nu \) can be obtained by \( Nu = (\int S \nu \theta dS) / S \) where \( S \) is the area of the airship, \( \theta \) is the angular position.

(a) The effect of \( Re \) on \( Nu \) with \( e = 2 \) and \( \alpha = 0° \)  
(b) The effect of \( e \) on \( Nu \) with \( \alpha = 0° \) and \( Re = 1 \times 10^7 \)

(c) The effect of \( \alpha \) on \( Nu \) with \( e = 2 \) and \( Re = 1 \times 10^7 \)

Figure 4. The relation of \( Nu \) vs. \( Re \), \( e \), and \( \alpha \).
Figure 4a shows that $Nu$ clearly increases with the increase of $Re$. According to the definition of the Reynolds number, that is, $Re = Ul/\nu$, where $U$ is the velocity of the fluid, $l$ is the characteristic length of the airship, and $\nu$ is the kinematic viscosity of the fluid. When $L$ and $\nu$ are constant, $U \propto Re$. The larger the value of $Re$, the larger the value of $U$ around an airship, which results in the removal of more heat and the increase of $Nu$.

Figure 4b demonstrates that $Nu$ decreases with the increase of $e$. According to the definition of $e$ above, the shape of an airship is close to a sphere when $e$ is small. However, the shape of an airship is close to a flat plate as $e$ increases. References [35–37] indicate that a vortex occurs in the tail region of a sphere while a uniform flow passes over a sphere, thereby resulting in enhanced convection heat transfer.

Figure 4c indicates that $Nu$ increases with the increase of $\alpha$. The presence of the angle of attack ($\alpha$) can cause changes in the flow structure around an airship, thereby resulting in a windward side, which eventually leads to a higher convective heat transfer.

Figure 5 shows the velocity contours and local velocity vectors around the airship with angle of attack of $0^\circ$ and $20^\circ$. The airflow flows from left to right. It is obvious that, at the front region, the velocity of the airflow decreases significantly, and then increases along the airship hull. It reaches a maximum value at the middle region of the airship hull and then gradually decreases. At the tail region, the velocity of the airflow is almost zero due to the separation of the airflow from the surface of the airship. Comparing Figure 5b with Figure 5a, it can be seen that the flow field structure around the airship is changed due to the existing of angle of attack. On the windward side, the position where the velocity of the airflow reaches its maximum moves backward, and in the leeward side, it shows an opposite trend. The change of flow field structure around the airship is the root reason for the change of forced convection heat transfer.

Figure 6. Fitting points and fitting surface.
3.2. Formula Fitting

3.2.1. Horizontal State

The horizontal state is the main state in a flight course. Thus, investigating the forced convection heat transfer around an ellipsoidal airship under horizontal state is important. Assume $\alpha = 0^\circ$, the values of $Re$ and $e$ are determined according to Table 2. The average heat transfer in terms of the $Nu$ around an ellipsoidal airship can be written as a power law equation

$$Nu = c_1Re^{c_2}e^{c_3}$$  \hspace{1cm} (5)

where $c_1$, $c_2$ and $c_3$ are constant coefficients.

Based on the data obtained from the aforementioned simulation results, a new correlation of $Nu$ with a determination coefficient ($r^2$) of 0.9996 and a root mean squared error (RMSE) of 2054 is proposed via MATLAB R2018a. The fitting points and fitting surface are shown in Figure 6.

The values of the fitting parameters are listed in Table 3. The value of $c_1 \sim c_3$ is introduced into Formula (5) to obtain Formula (6)

$$Nu = 0.0161Re^{0.8543}e^{-0.0454}$$  \hspace{1cm} (6)

where $Re \in [1 \times 10^7, 2.0 \times 10^8]$ and $e \in [2, 6]$.

| $e$  | $Re$        | Calculated Results by Formula (6) | Numerical Results by CFD | Error/$(\%)$ |
|------|-------------|----------------------------------|--------------------------|--------------|
| 2.2  | $1 \times 10^7$ | 14,838                           | 14,989                   | 1.01         |
| 3.75 | $5.75 \times 10^7$ | 64,543                           | 63,685                   | 1.33         |
| 4.25 | $5.75 \times 10^7$ | 64,177                           | 63,202                   | 1.52         |
| 5.3  | $2.0 \times 10^8$ | 184,295                          | 18,4979                  | 0.37         |

The model of the non-fit points is numerically simulated to validate the correctness of Formula (6). Table 4 compares the values of $Nu$ calculated by Formula (6) with those obtained from the simulation results. The calculated results agree well with those of the simulation results.
3.2.2. State Modification

The problem of changes of attack angle of a stratospheric airship is an important subject on the research of the Stratospheric Airship Platform. Li [38] pointed out that the airship reaches its stable attack angle, and that the attack angle is usually large. Then, the airship ascends at its stable attack angle. So, it is necessary to investigate the forced convection heat transfer of the airship at a certain attack angle.

The definition of \( K \) is introduced in this part and can be expressed in the form of

\[
K(Re, \varepsilon, \alpha) = \frac{Nu(Re, \varepsilon, \alpha)}{Nu(Re, \varepsilon)}
\]

Figure 7 shows the relation between \( K \) and \( \alpha \) \((Re = 1 \times 10^7)\). Clearly, \( K \) increases with the increase of \( \alpha \) regardless of the value of \( \varepsilon \). The larger the attack angle, the greater the difference. \( K \) increases with the increase of the \( \varepsilon \) for a given \( \alpha \), especially at higher \( \alpha \).

Figure 8 shows the relation between \( K \) and \( \alpha \) \((Re = 1 \times 10^7)\). For example, \( K \) reduces from 1.052 to 1.033 with \( Re \) changes from \( 1 \times 10^7 \) to \( 2.0 \times 10^8 \) when \( \alpha = 20^\circ \). This result means that the effect of \( Re \) on \( K \) can be ignored. \( K \) increases with the increase of \( \alpha \) for a given \( Re \). For instance, the value of \( K \) at \( \alpha = 20^\circ \) and \( \alpha = 5^\circ \) is 1.053 and 1.004, respectively, with a difference of 4.8% when \( Re = 1 \times 10^7 \).
The correction factor $K$ can be simplified to $K(e, \alpha)$ based on the above analysis. The mean value of $K$ corresponding to different $Re$ is taken as the final value of $K$. Based on the data obtained from the above simulation results, a correlation of the correction factor $K$ with a determination coefficient ($r^2$) of 0.9995 and a RMSE of 0.0005286 is proposed via MATLAB R2018a. The formula can be written as

$$K = 10^{-4} \left(2.17e^2 + 1.274\alpha^2 - 7.653\alpha - 1.01\alpha + 9991\right)$$

(8)

where $e \in [2, 6]$ and $\alpha \in \left[0^\circ, 20^\circ\right]$.

According to the above analysis, the forced convection heat transfer for stratospheric airship involved flight state can be calculated by the following empirical correlation

$$Nu = 0.0161KRe^{0.8543}e^{-0.0454}$$

(9)

The correctness of Formula (9) is likewise validated, and the results are listed in Table 5.

| $e$   | $Re$          | $\alpha$($^\circ$) | Calculated Results by Formula (9) | Numerical Results by CFD | Error($\%$) |
|-------|---------------|---------------------|-----------------------------------|--------------------------|-------------|
| 2.2   | $1 \times 10^7$ | 5                   | 14,855                            | 15,077                   | 1.47        |
| 3.75  | $5.75 \times 10^7$ | 10                 | 65,254                            | 64,410                   | 1.31        |
| 4.25  | $5.75 \times 10^7$ | 10                 | 64,915                            | 65,923                   | 1.53        |
| 5.3   | $2.0 \times 10^8$ | 20                 | 193,524                           | 18,792                   | 2.98        |

As mentioned above, for the external forced convection heat transfer of an ellipsoidal airship flying with a certain angle of attack, there is no specific correlation available yet. Most of the researchers conducted their researches without considering the effect of flight state. Figure 9 compares the values of the average Nusselt number obtained from Formula (9) with those taken from the literatures [11,30,39]. The geometry models used in these literatures are the same as or close to the one used in present study. They are all ellipse. It can be noted that the results of the present study show a consistent performance trend with literatures. Generally, the present results with $\alpha = 20^\circ$ are higher than those of existing correlations, especially at a higher Reynolds number, where the difference reaches a maximum of about 30 percent compared with Dai. In the thermal design period, the effect of flow state cannot be ignored.

![Figure 9](image_url)  

**Figure 9.** Comparison of values of the Nusselt number from the present study with $\alpha = 20^\circ$, with those from the literatures.
4. Conclusions

A numerical survey is conducted to explore the forced convection heat transfer of a full-scale ellipsoidal airship. The effects of angle of attack, Reynolds number and length to diameter ratio on heat transfer are investigated. An empirical correlation describing the heat transfer of an ellipsoidal airship was developed. Several conclusions were drawn after analyzing the results:

1. The change of flow field structure around the airship is the root reason for the change of forced convection heat transfer.
2. The average Nusselt number increases with the increase of $Re (1 \times 10^7$ to $2.0 \times 10^8$), decreases with the increase of $e$ (2 to 6), and increases with the increase of $\alpha$ (0 to $20^\circ$).
3. In the present study, the results show a similar performance trend with the existing correlations, and at higher Reynolds number, the results of the present study are higher by 30 percent than those of Dai with $\alpha = 20^\circ$.
4. $K$ increases with the increase of $e$ and $\alpha$, and the results with $\alpha = 20^\circ$ have about a 6 percent difference than that without angle of attack. Flight state is an important factor to be considered in the thermal design period of an ellipsoidal airship.

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