Simulation of Aircraft Electro-Thermal Windshield Heat Transfer with Artificial Heat Source Method

HAN Wangchao[1*], *REN Ruidong*[2]

1. AVIC Xi'an Aircraft Design and Research Institute, Xi'an 710089, P.R. China;
2. Chinese Flight Test Establishment, Xi'an 710089, P.R. China

(Received 9 March 2023; revised 22 August 2023; accepted 28 August 2023)

Abstract: An artificial heat source (AHS) method is proposed to solve the problem of negative volume or non-physical property errors that happens in the process of heat transfer simulation of the aircraft electro-thermal windshield which has a thin film heater embodied in its multilayer structure. Since the thickness of the thin film heater is very small (10^{-9}—10^{-7} m), the temperature gradient between the film heaters and the time delay generated by heating the film heater can be ignored, and the thermal diffusivity can be set to infinity for decoupling the thickness relationship between the real heat source and the mesh model in the simulation. Heat transfer simulations are conducted on the aircraft electro-thermal windshield mesh models with different thicknesses of the film heater. The results show that with the AHS method, mesh thicknesses of the thin film heater has no influence on the results of the simulation, and the problem of negative volume or non-physical property errors is solved spontaneously.

Key words: electro-thermal windshield; film heater; heat transfer; artificial heat source (AHS) mothod

CLC number: V211.3 **Document code:** A **Article ID:** 1005-1120(2023)S1-0050-05

0 Introduction

The structure of the aircraft electro-thermal windshield is a typical multilayer with a film heater and some temperature sensors embedded in it[1-2]. With the margin between the feedback of the temperature sensors and the target control temperature, a controller can be set the power input to the heater to make the temperature of the windshield in a reasonable range[3-4].

Tests and simulations need to be conducted in the process of designing an aircraft windshield electro-thermal anti-icing and anti-fogging system to evaluate the rationality of the power input and the heating law of the system. Rodert[5] measured the heat requirements of an electro-thermal windshield in the different air temperatures and free stream speed with the icing wind tunnel tests and flight tests. Jones et al.[6] got the heat requirements of an electro-thermal windshield with flight tests and made a comparison with the theoretical value. Through the flight tests, James et al.[7] found when the rate of descent was over 5 000 feet per minute, the temperature of the inside surface of the windshield remained approximately constant. Kleinknecht[8] conducted a flight test to establish the heat requirements of the windshield for ice prevention with the different angles between windshield and thrust axis. Xu[9] made a wind tunnel test to study the heat requirements with the different convective heat transfer coefficients. Hu et al.[10] conducted a ground test to study the anti-icing and anti-fogging functions of an aircraft windshield heating system. There were lots of experiment studies about aircraft windshield heating system, but numerical simulation studies in this field are rare. Han et al.[11] invented a flux-temperature boundary condition to solve the transient heat transfer process of the windshield, but as the total heat transfer coefficients are used in the method, the parameters relating time

*Corresponding author, E-mail address: h_011@126.com.

How to cite this article: HAN Wangchao, REN Ruidong. Simulation of aircraft electro-thermal windshield heat transfer with artificial heat source method[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2023, 40(S1): 50-54.
http://dx.doi.org/10.16356/j.1005-1120.2023.S1.005

(e.g. the period of the temperature vs heating process) has some deviation in theory.

Compared with the other multilayer, the thickness of the film heater embedded in the windshield is so tiny (10^{-9}—10^{-7} m[12]), and negative volume and non-physical property errors will be generated in the heat transfer simulation of the curved surface windshield, and the time cost is huge.

To solve the above-mentioned problems, the temperature gradients of the materials adjacent to the film heater were analyzed based on the Fourier's law of heat conduction, and a conclusion was drawn that the temperature gradient between the film heater and the time delay generated by heating the film heater could be ignored compared with the materials adjacent to the film heater. Based on this conclusion, an artificial heat source (AHS) method was proposed and verified by conducting heat transfer simulations with curved surface windshield mesh models which had different thicknesses of artificial film heater.

1 Heat Transfer Process of the Windshield

Aircraft electro-thermal windshield is always a multiplayer structure. Fig.1 is a schematic of a typical aircraft windshield structure. The film heater is set in the inside surface of the outer layer of the windshield[11], and two or three temperature sensors are embedded in the adjacent layer of the film heater to monitor the temperature of the heater. The thicknesses and physical properties of the materials is listed in Table 1.

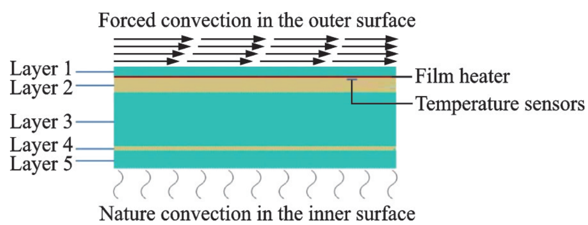

Fig.1 Typical configuration of electro-thermal windshield

Table 1 Material and thickness of layers in electro-thermal windshield

Layer	Material	Thickness/m	λ /(W•(m•K)$^{-1}$)	C_p/(J•(kg•K)$^{-1}$)	ρ /(kg•m^{-3})
1	Inorganic Glass	3×10^{-3}	1.22	900	2 490
Heater	ITO	10^{-9}—10^{-7}[12]	8.7 [13]	0.36×10^{3}[13]	7.04×10^{3}[13]
2	PU	4.35×10^{-3}	0.22	2 080	1 080
3	Inorganic Glass	15.00×10^{-3}	1.22	900	2 490
4	PU	1.25×10^{-3}	0.22	2 080	1 080
5	Inorganic Glass	5.00×10^{-3}	1.22	900	2 490

Under flight conditions, the windshield of an aircraft is enduring three effects, which are the forced convection in the outer surface of the windshield, nature convection in the inner surface of the windshield, and the heat generated by the film heater. For the purpose of making the temperature of the film heater in a reasonable range, the film heater is controlled to be on or off with the feedback temperature of the embedded sensors. So the heat transfer process of the aircraft electro-thermal windshield is a transient heat transfer process with an embedded film heater in the multiplayer, and the process can be described as[14]

$$\frac{\partial T}{\partial t}=\frac{\lambda}{\rho C_p}\nabla^2 T+\frac{\dot{\varnothing}}{\rho C_p} \tag{1}$$

$$-\lambda\left(\frac{\partial T}{\partial n}\right)_w=h\left(T_w-T_f\right) \tag{2}$$

Now, the AHS method would be derived by the Fourier's law of heat conduction and the definition of the specific heat. Suppose thickness of any layer of the windshield is δ, and the average temperature gradient of the layer is ΔT. Therefore, according to the Fourier's law of heat conduction, there is

$$\Delta T=\frac{1}{\lambda}q\delta \tag{3}$$

where q is the heat flux of the surface.

Similarly, with the definition of the specific heat, the average time delay τ by making the temperature of the layer abovementioned increasing 1 K can be evaluated by

$$\tau=\frac{\rho C_p\delta}{q} \tag{4}$$

Assume that the thickness of the film heater is 10^{-7} m, and half of the heat flux flows to the outer surface of the windshield, and the other half of the heat flux flows to the inner surface of the windshield. This assumption is only for qualitative analysis. In fact, the heat fluxes to the outer surface and the inner surface are changing with the outer atmosphere conditions of the windshield. With the typical surface power density 8 000 W/m^2[13], the ΔT and τ in Table 1 can be obtained from Eqs.(3, 4). The results of ΔT and τ were listed in Table 2.

Table 2 Qualitative analysis of heat transfer in the film heater and its adjacent materials

Layer	Material	Thickness/m	ΔT/K	τ/s
1	Inorganic glass	3×10^{-3}	9.836	1.681
Heater	ITO	10^{-7}	9.195×10^{-5}	3.17×10^{-5}
2	PU	4.35×10^{-3}	79.091	2.443

According to Table 2, the sizes of ΔT and τ of the film heater can be ignored with respect to the same parameters of adjacent materials. This can make the derivation that the heat flux can flow through the film heater with no resistance and delay. Conversely, if there is a heater that the heat flux can flow through it with no resistance and delay, the heater can be treated as the film heater of the windshield.

Based on this conclusion, in the numerical analysis of the heating process of the windshield, a virtual heater can be constructed by setting the density and specific heat capacity of the heater to an infinitesimal value, and the thermal conductivity of the heater to an infinite value, in place of the real film heater (that is, the thermal diffusivity is set to be infinity). For simplicity, this process is named as the AHS method. With the AHS method, the thickness of the artificial heater has no influence on the process of windshield mesh generation and heat transfer simulation. At the same time, the negative volume and non-physical property errors mentioned above can be solved spontaneously.

2 Simulation Tests

Simulations of electro-thermal windshield heat transfer process were conducted with three different thicknesses of the film heater (Table 3), and the mesh model is illustrated in Fig.2. Since the thickness of heater is so small, the illustration cannot reflect the thickness of the heater, so the three cases in Table 3 have the same illustration.

Table 3 Properties of the film heater in the mesh models for validating AHS method

Case	Thickness/m	λ/(W·(m·K)$^{-1}$)	C_p/(J·(kg·K)$^{-1}$)	ρ/(kg·m^3)
1	10^{-7}	8.7 [13]	0.36×10^3[13]	7.04×10^3[13]
2	10^{-5}	10^6	10^{-6}	10^{-6}
3	10^{-4}	10^6	10^{-6}	10^{-6}

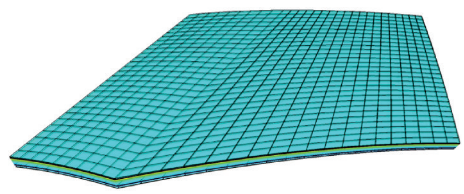

Fig.2 Mesh model of electro-thermal windshield

The surface power density of the heater is set as 8 000 W/m^2[13], and the heater is on when its temperature is less than 308.15 K(35 ℃) and is off when its temperature is greater than 316.15 K (43 ℃).

The convective heat transfer boundary condition is set at the outer and the inner surfaces of the windshield. For the outer surface, the convection coefficient is set as 100 W/(m^2·K), and the free stream temperature is set as 263.15 K. And for the inner surface, the convection coefficient is set as 11.375 W/(m^2·K)[15], and the cockpit temperature is set as 294.15 K. The initial temperature of the windshield is set as 263.15 K.

Fig.3 shows the temperature change regulation of the three cases with the heating process. In Fig.3, "Tw1" and "Tw2" mean the inner and outer surface temperatures of the heater, respectively, and "case 1" "case 2" and "case 3" mean the different cases listed in Table 3.

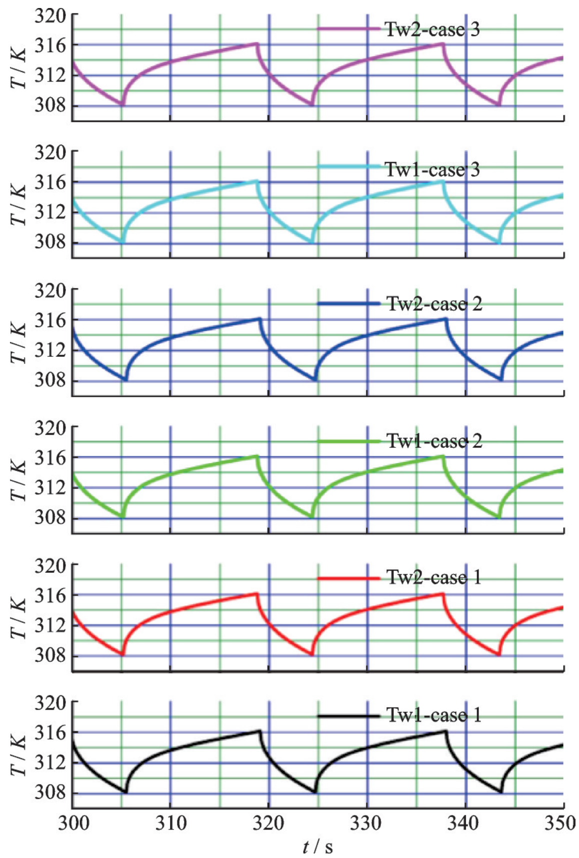

Fig.3 Film heater temperature vs heating process

The following conclusions can be drawn from Fig.3.

(1) For the same case with the same thinness of the heater, the inner and outer surface temperatures of the heater are equal, and they have the same regulation with the heating process.

(2) With different thinnesses of heaters, the inner or outer surface temperature of the heater has the same regulation with the heating process.

Hence, the thickness of the heater in the mesh model has no effect on the heat transfer simulation process.

3 Conclusions

The influence of the film heater on the heat transfer process of the aircraft electro-thermal windshield was studied, and a conclusion was drawn that the heat flux can flow through the film heater with no resistance and delay. Based on this conclusion, a new AHS method was derived from constructing an artificial film heater with an infinite thermal diffusivity. With the AHS method, the thickness of the real film heater could be decoupled with the thickness of the mesh model film heater, and the negative volume and non-physical property errors that happened in the simulation process were solved spontaneously.

References

[1] LIPSKI V L. Windows and windshields: AC 25.775-1[R]. Washington DC: Federal Aviation Administration, 2003.

[2] HEINRICH A, ROSS R, ZUMWALT G, et al. Aircraft icing handbook: DOT/FAA/CT-88/8-1 [R]. Washington DC: Federal Aviation Administration, 1991.

[3] Boeing Company. B737NG aircraft maintenance manual[M]. [S.l.]: Boeing Company, 2003.

[4] TANG Meian. Operation and maintenance of Boeing 757 cockpit's windshield glass[J]. China Civil Aviation, 1996(1): 43-44. (in Chinese)

[5] RODERT L A. Investigation of an electrically heated airplane windshield for ice prevention: NASA/SR-1939-105[R]. Washington DC: NASA Langley Research Center, 1939.

[6] JONES A R, HOLDAWAY G H, STEINMETZ C P. A method for calculating the heat required for windshield thermal ice prevention based on extensive flight tests in natural icing conditions: NASA/TN-1947-1434[R]. Washington DC: NASA Langley Research Center, 1947.

[7] JAMES S, ZERBE J E. A method for calculation the heat required for the prevention of fog formations on the inside surface of single-panel bullet-resisting windshields during flight: NASA/TN-1947-1301[R]. Washington DC: NASA Langley Research Center, 1947.

[8] KLEINKNECHT K S. Flight investigation of the heat requirements for ice prevention on aircraft windshields: NACA RM No.E7G28[R]. Cleveland Ohlo: Flight Propulsion Research Laboratory, 1947.

[9] XU Jiajia. Studies of electro-thermal anti-icing system for aircraft windshield[D]. Nanjing: Nanjing University of Aeronautics and Astronautics, 2011. (in Chinese)

[10] HU Yang, DANG Qi, CHANG Hongliang. Research on ground test of aircraft windshield heating system[J]. Aeronautical Science & Technology, 2014, 25(3): 67-70. (in Chinese)

[11] HAN Wangchao, ZHU Yongfeng, CHANG Hongliang. Simulation of heat transfer problem of a multilayer structure with a cyclic thin film heater source[J].

Acta Aerodynamica Sinica, 2016, 34(3): 313-316. (in Chinese)

[12] WU Yutao, WENG Xiaolong, DENG Longjiang. Transmittance and electromagnetic shielding of ITO films deposited at low temperature[J]. Chinese Journal of Vacuum Science and Technology, 2006, 26(5): 372-376.

[13] MEDVEDOVSKI E, ALVAREZ N, YANKOV O, et al. Advanced indium-tin oxide ceramics for sputtering targets[J]. Ceramics International 2008, 34(5): 1173-1182.

[14] HUANG J R, KEITH T G, JR DEWITT K J. Numerical simulation of an electrothermally de-iced aircraft surface using the finite element method: AIAA-91-0268[R]. Reno, Nevada: AIAA, 1991.

[15] Society of Automotive Engineers. Ice, rain, fog, and frost protection: SAE AIR1168/4[EB/OL]. (2014-01-14). http://www. sae. org/technical/standards/AIR1168/4A.

Author Mr. HAN Wangchao received his M.S. degree in fluid dynamics from Northwestern Polytechnical University in 2008. Then he has been employed in AVIC Xi' an Aircraft Design and Research Institute for studying and designing aircraft anti-icing and de-icing system. His research interests are aircraft electro-thermal anti-icing or de-icing system numerical simulation and their control regulations.

Author contributions Mr. HAN Wangchao designed the study, complied the models, conducted the analysis, interpreted the results and wrote the manuscript. Mr. REN Ruidong participated in the discussion of the problems be studied in the manuscript, and gave valuable suggestions for conducting the analysis. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: XU Chengting)

基于虚拟热源法的飞机电热风挡传热数值仿真

韩王超[1],任瑞冬[2]

(1.中国航空工业集团公司第一飞机设计研究院,西安 710089,中国; 2.中国飞行试验研究院,西安 710089,中国)

摘要: 为解决弧面外形的飞机电热风挡传热数值仿真过程中因薄膜热源对应的网格厚度过小易于导致的网格负体积、非物理解等问题,基于电热风挡薄膜热源厚度范围(10^{-9}~10^{-7} m)较其相邻多层介质厚度较小这一事实,结合傅里叶传热理论分析,构建了一种针对飞机电热风挡传热数值仿真薄膜热源处理的虚拟热源法。该方法通过设定薄膜热源虚拟物性参数弱化薄膜热源实际厚度对其相应仿真网格厚度的约束,从而实现薄膜热源厚度与其对应网格厚度的解耦。利用该方法对2种不同薄膜热源网格厚度的电热风挡模型进行了非稳态传热数值仿真,并将仿真结果与按实际薄膜热源厚度设定网格厚度及物性参数的电热风挡模型仿真结果进行对比发现,虚拟热源法求解的仿真结果与按常规设置求解的仿真结果在温度和时间两个维度上均吻合。因此,在求解类似电热风挡这种具有薄膜内热源的非稳态传热问题时,可在构建网格模型时按需设定薄膜热源网格厚度,并在求解时采用虚拟热源法,以避免网格负体积或非物理解问题的发生。

关键词: 电热风挡;薄膜热源;传热;虚拟热源法