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Similarity criteria of target thermal radiation characteristics and their application to infrared radiation of jet engine exhaust system

Dongla Mo*, Shiguo Chen, Lihai Chen, Ping Wang, Jingcheng Shi

Xi'an Vincentech Co. Ltd., China

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ABSTRACT

In this study, the similarity criteria for thermal radiation characteristics of the target, such as gas flow, heat transfer, mass transfer and thermal radiation coupling effect, were considered. Only in the case where the criteria are based on the similarity of geometry, gas flow, heat transfer and component transportation, can the similarity of thermal radiation be possible. Similarity criteria of different physical mechanisms were obtained by adopting a dimensionless analysis of their governing equations. Every similarity criterion features the impact of each physical mechanism on thermal radiation of target. Thermal radiation similarity theory was applied to a single duct exhaust system and after theoretical analysis, the dominant similarity criteria were selected, while the others were neglected. It was pronounced that there are only three dominant similarity criteria for single duct exhaust system: a) the nozzle pressure ratio, b) the total temperature of the inlet and c) the optical depth. Three cases were simulated numerically using k-ε turbulent viscosity model and backward Monte-Carlo method for the verification of the above conclusion. The boundary conditions and characteristic lengths of the three cases were different but the dominant similarity criteria were respectively the same. Therefore, the results coincided adequately with each other, conclusion that corresponds to the predictions of the theory.

1. Introduction

As infrared treat of military target is becoming increasingly severe, research on infrared radiation (IR) is becoming of utmost importance to eliminate the threat and sustain the survivability, which becomes the key link of stealth technology [1]. At present, a considerable number of researches focused on infrared signal characteristics of target have been published. In 1991, the NIRATAM (NATO infrared air target model) was developed by the NATO-organized RSG6, members of which investigated the infrared signatures of aircrafts, helicopters and antiaircraft missiles [2]. Pan et al. [3] proposed a calculation method for IR intensity containing uncertain information and analyzed process of non-probabilistic reliability. Cline [4] described the successful validation of the F/A-22 IR signature prediction model by using in-flight IR radiometric measurements. This article provides a new perspective of similarity theory concerning the research of infrared signal characteristics of target.

Similarity theory has been widely applied in many fields, such as fluid dynamics, hydraulics, microwave, thermal conductivity and engineering thermodynamics. However, the previous applications (within the knowledge of the authors) of similarity theory to thermal radiation are limited and incomplete.

Refs. [5–7] present the theoretical and experimental results of the investigation of similarity for thermal radiation from heated jets. It was concluded that the principal condition for the radiation similarity is the similarity of the temperature and the concentration fields in the near nozzle region. A universal function, based on optical similarity relationship, was also developed, but the computational accuracy was barely satisfactory (the discrepancy was approximately 20 or 30%). Another past research investigated scaling and self-similarity properties of infrared emission from heated dust wind and deduced that the controlled parameter was the overall dust optical depth [8].

However, for a wide range of targets, the thermal radiation depends on a variety of physical mechanisms, such as gas flow, heat transfer and mass transfer. Previous research has not presented clear coupling effects and similarity criteria of these physical mechanisms. In present study, author's purpose was to develop a complete similarity theory of thermal radiation from gas flow, heat transfer, mass transfer and radiation coupling environment. Further objective was to obtain relative similarity criteria, adjustable to a wide range of targets. Through dimensionless analysis of the coupling governing equation, the similarity criteria for multi physical mechanisms were summarized.

It is a great advantage of the similarity theory that it can offer an efficient method to simplify all multi physical problems. With the

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* Corresponding author.
E-mail address: dongla.mo@vincentech.net (D. Mo).

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similarity theory contribution, individuals can study the aerodynamic performance of the aircraft in the wind tunnel rather than in the sky, eliminating a high amount of costs. For a specific target, the calculation of thermal radiation is complex desideratum since many variables must be taken into consideration. These variables can be combined into several dimensionless numbers, namely similarity criteria, by using the principle of similarity. Every similarity criterion includes a clear physics meaning and characterizes the impact of a physical mechanism on thermal radiation from target. The impact of some physical mechanisms is insubstantial thus negligible, while the impact of others is dominant and accountable. By this distinction, all multi physical problems-are considerably simplified.

From the analysis of dimensionless governing equations, the similarity criteria for thermal radiation characteristics of the target were earlier proposed in this article. In the latter part of this paper, thermal radiation similarity theory was applied to a single duct exhaust system and it was deduced that the dominant similarity criteria are the nozzle pressure ratio, the total temperature of inlet and the optical depth. The numerical simulation results, obtained by *k*-*ε* turbulent viscosity model and backward Monte-Carlo method were in perfectly agreement with this conclusion.

Nomenclature

Latin letters		η	wavenumber
c_V	heat capacity at constant volume	θ	detection angle
c_p	heat capacity at constant pressure	κ	absorption coefficient
C_j	mole concentration of component *j*	λ	wavelength
D_j	diffusion coefficient of component *j*	μ	dynamics viscosity coefficient
e	internal energy	ρ	density
$\dot{H}$	heating rate	σ	Stefan constant
I	integral radiation intensity	τ	transmittance
I_λ	spectral radiation intensity	Ω	the direction angle of radiation
k	thermal conductivity coefficient		
l	characteristic length	Subscripts	
L_η	spectral radiance	∞	free stream
M_j	molecular weight of component *j*	b	black body
p	pressure	e	environment
p_j	partial pressure of absorption component *j*	j	component *j*
s	radiation transfer distance	s	solid
S	line intensity	w	wall
T	temperature	in	inlet
v	velocity	out	outlet
x_i	coordinate tensor	0	Standard variable
X	mole fraction		
Y	mass fraction	Dimensionless numbers	
		Sr	Strouhal number
Greek letters		Re	Reynolds number
γ	ratio of specific heat capacity	Ma	Mach number
γ_D	Doppler halfwidth	Pr	Prandtl number
γ_L	Lorentz halfwidth	Nu	Nusselt number
ε	emissivity	St	Stefan number
		Sc	Schmidt number

2. Theory: similarity criteria for thermal radiation characteristic of target

The thermal radiation of gas flow, heat transfer, mass transfer and radiation coupling environment is closely correlated to multi physics mechanisms and multi variables. The intensity of radiation is related to temperature, emissivity and area of the source while radiation transfer is affected by concentration of gas molecules. Therefore, the thermal radiation similarity must be based on the similarity of geometry, gas flow, heat transfer and component transport.

2.1. Similarity criteria for gas flow field

The dimensionless N-S equation is given by:

$$\begin{cases} \frac{\partial\bar{\rho}}{\partial\bar{t}} + \frac{1}{Sr_\infty}\frac{\partial}{\partial\bar{x}_i}(\bar{\rho}\bar{v}_i) = 0 \\ \frac{\partial}{\partial\bar{t}}(\bar{\rho}\bar{v}_i) + \frac{1}{Sr_\infty}\frac{\partial}{\partial\bar{x}_j}(\bar{\rho}\bar{v}_i\bar{v}_j) = -\frac{1}{\gamma Sr_\infty Ma_\infty^2}\frac{\partial\bar{p}}{\partial\bar{x}_i} + \frac{1}{Sr_\infty Re_\infty}\frac{\partial}{\partial\bar{x}_j}\left(2\bar{\mu}\bar{e}_{ij} - \frac{2}{3}\bar{\mu}\bar{e}_{kk}\delta_{ij}\right) \\ \frac{\partial}{\partial\bar{t}}(\bar{\rho}\bar{E}) + \frac{1}{Sr_\infty}\frac{\partial}{\partial\bar{x}_i}(\bar{\rho}\bar{E}\bar{v}_i) = -\frac{\gamma-1}{Sr_\infty[1+\gamma(\gamma-1)Ma_\infty^2]}\frac{\partial(\bar{p}\bar{v}_i)}{\partial\bar{x}_i} + \frac{\gamma(\gamma-1)Ma_\infty^2}{Sr_\infty(Re_\infty+1)}\frac{\partial}{\partial\bar{x}_j}\left[\bar{v}_i\left(2\bar{\mu}\bar{e}_{ij} - \frac{2}{3}\bar{\mu}\bar{e}_{kk}\delta_{ij}\right)\right] + \frac{\gamma(\gamma-1)Ma_\infty^2}{(\gamma-1)Pr_\infty Re_\infty Ma_\infty^2+1}\frac{\partial}{\partial\bar{x}_i}\left(\bar{k}\frac{\partial\bar{T}}{\partial\bar{x}_i}\right) \end{cases} \quad (1)$$

where the three equations indicate the conservation of mass, momentum and energy respectively. The similarity criteria of flow can be obtained from the dimensionless N-S equation as follows:

$$\begin{cases} \gamma = \frac{c_p}{c_V}, Sr_\infty = \frac{l}{v_\infty t}, Pr_\infty = \frac{\mu_\infty c_p}{k} \\ Ma_\infty = \frac{v_\infty}{\sqrt{\gamma RT_\infty}}, Re_\infty = \frac{\rho_\infty v_\infty l}{\mu_\infty} \end{cases}$$

For specific gas, the ratio of specific heat capacity γ is constant. Thermal conductivity coefficient *k* corresponds to low values and changes with temperature variations, but it is insensitive to pressure. For ideal gas, heat capacity c_p and viscosity coefficient μ depend on temperature. Therefore, Prandtl number (*Pr*) of gas mostly changes with temperature ranging between 0.6 and 0.7.

According to the above, the main similarity criteria of flow and convective heat transfer is *Sr*, *Ma*, *Re* and *Pr*, which characterize the unsteadiness, compressibility, viscosity and performance of heat transfer of flow respectively.

2.2. Similarity criteria for boundary condition

By taking into account the effects of boundary condition, the similarity criterion of boundary was summarized. In this paper, the boundary of flow field was divided into two categories of gas and solid boundary. Solid boundary includes adiabatic wall (AW), isothermal wall (IW) and non-isothermal non-adiabatic wall (NINAW). Gas boundary is an environment where the flow parameters are constant and hardly disturbed by the main flow.

The temperature of the adiabatic wall entirely depends on the flow field. The boundary condition of isothermal wall was $T = T_w$. Thus, the dimensionless internal energy is given by:

$$\bar{E} = \frac{E}{c_V T_\infty} = \frac{c_V T_w}{c_V T_\infty} = \frac{T_w}{T_\infty}, \quad (2)$$

which indicates that T_w/T_∞ is a similarity criterion for isothermal wall. For non-isothermal non-adiabatic wall, the heat dissipation contains conduction and thermal radiation. Hence, the heat transfer conservation equation is given by:

$$q = h\Delta T = k_s\frac{\partial T}{\partial n}\bigg|_{n=0} + \varepsilon\sigma T_w^4, \quad (3)$$

where k_s is the thermal conductivity of the wall, ε equals emissivity of the wall and σ corresponds to Stefan-Boltzmann constant. Two heat