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A simulation method of aircraft plumes for real-time imaging

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HIGHLIGHTS

- A real-time simulation method to predict the infrared feature of aircraft plumes.
- A modified C–G model to calculate the non-uniformly distributed parameters.
- The simulation method was validated by comparing with the CFD++.
- A good balance between simulation precision and computation efficiency.

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ABSTRACT

Real-time infrared simulation technology can provide a large number of infrared images under different conditions to support the design, test and evaluation of a system having infrared imaging equipment with very low costs. By synthesizing heat transfer, infrared physics, fluid mechanics and computer graphics, a real-time infrared simulation method is proposed based on the method of characteristics to predict the infrared feature of aircraft plumes, which tries to obtain a good balance between simulation precision and computation efficiency. The temperature and pressure distribution in the under-expansion status can be rapidly solved with dynamically changing flight statuses and engine working states. And a modified C–G (Curtis–Godson) spectral band model that combines the plume streamlines with the conventional C–G spectral band model was implemented to calculate the non-uniformly distributed radiation parameters inside a plume field. The simulation result was analyzed and compared with the CFD++, which validates the credibility and efficiency of the proposed simulation method.

1. Introduction

Systems featured with infrared imaging equipment usually possess higher precision, powerful anti-electromagnetic interference capability and better concealing ability; and they are widely applied in civil and military fields. A lot of infrared images are especially needed to satisfy the verification, design, test and evaluation requirements of these systems. Physical test methods can supply real infrared image snapshots of specific objects under certain weather conditions, while accompanying costs of a fairly large amount of human, physical and financial resources. Infrared modeling and simulation technology is promisingly the solution to cope with such problems [1].

An aircraft is usually a typical kind of target for detection; thus to predict the infrared feature of aircraft plumes in real-time is a significant part of the infrared imaging simulation of an aircraft. During its flight process, plumes produced by an engine exhaust system have a relatively large range of influence and become a vital source of infrared radiation to be detected from forward and rear ramp directions. Some infrared simulation systems can support the image generation of plume infrared radiation effects. For examples, a physics-based broadband scene simulation tool CAMEO-SIM [2–4], a naval ship infrared signature countermeasure and threat engagement simulator ShipIR/NTCS [5], a modeling software for whole aircraft signatures with plumes McCavity [6], the Composite Hardbody and Missile Plume project, The Joint Army Navy NASA Air Force (JANNAF) model SPIRITS [7], and so on. The infrared radiation signature of plumes is very complicated and it is related with an aircraft's flight status, its engine's working states and related characteristics parameters. The engine's fuel, the composition of combustion products and the surrounding atmospheric environment are also closely linked. In theory, to simulate the infrared radiation feature of exhaust plumes with high fidelity is very difficult. The usual simulation process is to obtain the temperature, pressure and composition concentration distribution of plumes

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first by a flow field solution, and then to implement the calculation of infrared radiation features. There are two ways to simulate a plume fluid field. One is to establish a flow field model with simple geometry models and semi empirical formulas; the other one is to use CFD (Computational Fluid Dynamics) software for computation based on 3D grids. The former one is a fast solution way with less amount of calculation, but its simulation precision is not very high and the simulated plume has a relatively fixed shape. The latter can complete an accurate fluid field calculation, while the solution is too time-consuming to be used for a real-time simulation. Hence, we are aiming at finding a rapid fluid field solution method for aircraft plumes with enough precision, on the basis of which the real-time infrared feature prediction and image generation can be achieved.

In this paper, aiming at the balancing problem between simulation accuracy and calculation efficiency, the heat transfer principle, infrared physics, fluid mechanics, computer graphics and other disciplines are synthesized and a real-time infrared simulation method is proposed based on the method of characteristics. The temperature and pressure distribution of a plume fluid field can be solved based on the characteristics equation in the under-expansion status. Considering the non-uniformity of plumes field, we integrate the plume streamlines model and the conventional C–G (Curtis–Godson) spectral band model to get the infrared signature. The status parameters of an engine nozzle are introduced as the input parameters for plume field solution, so that the method has the ability to simulate the plume infrared feature which is dynamically changed with different flight status parameters. Impacts of different parameters on the plume radiation characteristics are analyzed based on our simulation results. And the simulation accuracy and computation efficiency are compared with CFD commercial software CFD++, which validated the credibility of our simulation model.

The remainder of the paper is organized as follows. In Section 2, a literature review is provided. In Section 3, our real-time simulation process for the plume infrared imaging is introduced. In Section 4, the method of characteristics is applied to solve the temperature and pressure distribution of a plume field. In Section 5, a modified C–G spectral band model is utilized to calculate the infrared radiation distribution of plumes. The simulation results of two typical cases are analyzed and compared in Section 6. In Section 7, a summary is presented.

2. Literature review

Limited physical experiments cannot provide infrared radiation distribution of plumes under all working cases, while numerical simulation can solve the flow field parameters of plumes under various conditions to provide data which cannot be attained in physical experiments. Meanwhile, the particle system, as one of the most successful graphic algorithms to simulate irregular fuzzy objects, is widely used in plume IR imaging. In Cook's research, a computational algorithm was described for direct numerical simulation (DNS) of a reactive plume in spatially evolving grid turbulence [8]. To give more details of the plume behavior under various situations, Li studied aerodynamics for thermally-induced plumes numerically with CFD [9]. Misaki and Tanaka conducted numerical simulations of laser-produced plumes to model their generation and dynamics in 2011 [10]. In the same year, Yuan utilized Gambit software to generate unstructured grids and got a physical model in Fluent which was made of a turbulence model and a combustion model. Based on those, he obtained a simulation of flow field data in Fluent [11]. In 2010, Yan presented an effective simulation method for real-time simulation of 3-dimensional missile plumes based on geometrical modeling or particle system modeling. He used a particle emission plate and velocity segmentation to enhance the hierarchy of the missile plume as well as providing an optimal trade-off between realistic visual appearance and real-time rendering [12]. CFD based numerical simulation methods emphasize the accurate calculation of plume field parameters, which is, however very time consuming and not suitable for real-time imaging. The particle system can be used for real-time rendering of special effects; but properties of physical fields cannot be precisely reflected without the support of physical mechanism based calculation. Therefore, trying to balance between simulation precision and computation efficiency, we hope to provide a method which cannot only be used in real-time imaging but also reflect the plume radiation characteristics with a relatively high precision.

In recent twenty years, a lot of infrared radiation modeling and simulation methods aiming at various targets, background environment have been systematically set up. Commercial software is developed on a large scale. For example, CHAMP was invented by KHILS in late 1980s. It was used for generating infrared radiation characteristics of complex targets, such as missiles with tail, aircrafts with multiple warhead-boosters at bottom [13]. SensorVision is a VEGA-based application that produces IR scenes in real time with a certain amount of simplifications in order to obtain the real time capacity [14]. CAMEO-SIM is an advanced IR program aiming at producing high fidelity physics based images originally applied to camouflage assessments [15,16]. RadThermIR is a 3-dimensional (with some restrictions) heat transfer program that uses Finite Difference Methods to predict the temperature distribution for a target and after that also predict the IR radiance [17]. ShipIR/NTCS, developed by W.R. Davis Engineering Ltd, is a comprehensive software package for predicting the infrared signature of naval ships in their maritime background. The software includes a generic imaging seeker model and IR flare countermeasure deployment model to simulate the engagement between a ship, its flare tactic and an infrared-guided missile [18].

The method of characteristics is a technique for solving partial differential equations. It's widely used in many fields of science. Douglas studied convection-dominated diffusion problems by combining the method of characteristics with finite element and finite difference methods [19]. Ewing modified the method of characteristics to give a convergence analysis of an approximation of miscible displacement in porous media [20]. Takamoto developed a new numerical scheme for resistive relativistic magnetohydrodynamics with this method [21]. The Curtis–Godson approximation estimates the transmittance along an inhomogeneous raypath using the transmittance across a single layer described by a mean pressure, temperature, and absorber amount, which can obtain relatively greater radiance accuracy [22]. Based on the Curtis–Godson approximation, Stephen presented theoretical formulations of radiation band models for general nonuniform optical paths [23]. Kim proposed a weighted sum of gray gases model (WSGGM)-based low-resolution spectral model for calculating radiation transfer in combustion gases to estimate self-absorption of radiation energy in one-dimensional opposed-flow flames and compared with the results of a narrow-band model based on the Curtis–Godson approximation [24]. André proposed a method to estimate Malkmus statistical narrow band (SNB) model parameters of nonuniform optical paths in gases and the nonuniform approximation was shown to enable the computation of transmissivities and radiation intensities with accuracy similar to or higher than those achieved by the Curtis–Godson one [25].

Based on above, we utilized the method of characteristics to predict the plume infrared radiation features and a modified C–G spectral band model to consider the non-uniformly distributed parameters inside the plume field.