On Rarefied Plumes

Subjects: Others
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Recent progress on rarefied jet, jet impingement, and total impingement loads are summarized here. Those investigations are performed by adopting the gaskinetic theory at the free molecular flow limit. The results include exact analytical solutions to the properties of flow field, surface load distributions, and overall surface loads. The flowfield solutions include density, velocity, temperature and pressure. The surface properties are based on the flowfield properties and they include shear stress, pressure and heat flux. The total surface loads include pressure, shear stress, torque, and various center-to-center distances. Different from many past work, many physical and geometric factors are includes explicitly, e.g., nozzle exit properties (velocity speed ratio, temperature, number density), surface reflection types, and locations. Evaluations on these analytical solutions are very fast via a computer, neither numerical simulations nor experimental measurements are needed. At far field, the nozzle exit degenerate as a point, and the exact solutions are even simpler. The expressions for the total loads at the free molecular flow limit can be used as anchoring values to estimate the total loads within the whole Knudson number range, i.e., continuum, velocity-slip and temperature-jump, transitional, and free molecular flows.

Keywords: jet, jet impingement, jet load, gaskinetic theory.

1. Introduction

Rarefied free jet and jet impingement flows have many applications in space and vacuum engineering. Here we only give several examples. The former is widely used to estimate rocket performance because a plume flow is one of its most important signatures. For the latter, if a jet impinges at a sensitive surface, e.g. a solar panel in a spacecraft, it may create extra force or heat loads on the surface and can damage it.

People have spent significant amount effort on analyzing such free jet and jet impingement flows. However, in a rarefied environment, it is quite challenging to study those flows. Rarefaction can be described by the Knudsen (Kn) number, which is defined as the ratio between the local mean free path to a characteristic length. According to different Kn number range, flows can be categorized as continuum, velocity-slip and temperature-jump, transitional, and free molecular.

It is generally accepted that more difficulties may increase to analyze jet and impingement flows as the Kn number increases. For the first two flow regimes, it is commonly agreed that the continuum flow assumption works well. There are exact solutions or models for these flows in these two flow regimes, and investigations are much convenient. For example, it is recommended to use the cosine law or the Simons model for rocket plume flows. There are numerous numerical simulation results and measurements in the literature for flows in the continuum or near-continuum flow regimes. However, for transitional and free molecular flow regimes, the continuum flow assumption breaks down, and investigations are relying on numerical simulations or experimental measurements. It is rather challenging to develop generally applicable formulas or models.

Since 2005, there have been much progress on investigating these jet [1][2][3][4][5][6] and jet impingement [7][8][9] flows. Different from the past investigations, those recent studies focused on the free molecular flow limit with the gaskinetic theory and exact solutions are obtained. The so-called gaskinetic theory uses velocity distribution functions and considers individual molecule's velocity. It is quite different from the continuum flow which assumes all molecules have the same velocities. Evidently within a small Knudsen number range, collisions among molecules are frequent and the continuum assumption is acceptable; however, for more rarefied gas flows with large Knudsen numbers, the gaskinetic theory is more reasonable.

Those recent studies on flows at the free molecular flow limit can be classified as three categories: free jet, jet impingement, and total jet impingement loads [10][11][12][13].

2. Development

Those recent studies on free jet flows adopted a constitutive relation between molecules' velocity components and distances: at the free molecular flow state without any collisions, all molecules travel along straight lines. As such, only special molecules from a spot on the nozzle exit can reach a specific plume field point. This relation allows variable transformation relations for integrations from velocity spaces to the nozzle exit geometries. As such, complex but exact expressions for plume flow field bulk properties, i.e., density, velocity components, pressure and temperatures are obtained. These exact solutions involve complex finite integrations which can be evaluated quite conveniently, and these solutions are validated with the direct Simulation Mote Carl (DSMC) [14] simulation results. As such, there is no need of numerical simulations and experimental measurements for neutral free molecular jet anymore. At far-field, the nozzle exit degenerates as a point source and these analytical solutions are greatly simplified. There is even no need to perform integration evaluations, instead, a simple hand calculator may be enough to compute the far-field properties.

Based on the solutions to free jets at the free molecular flow limit, the corresponding solutions [6-9] to free molecular jet impingement flows are further obtained. There are two types of plate surfaces, diffusive or specularly reflective. For the former, when a particle hits at a surface, it bounces back freely with equal probabilities to travel along any directions. For the latter, that particle bounces back with the tangential velocity component unchanged but the normal velocity component reversed. At a specific flow field point, there are two groups of molecules can arrive, one group from the nozzle exit, and the other from the plate surface. The treatments for a diffuse plate and a specularly reflective plate are different. The treatment for the latter is relatively complex and a "virtual" nozzle [9,11] is adopted which is a mirrored nozzle placed at the symmetric place at the other side of the plate. There are two sets of exact solutions to the jet impingement flows, one set is for the flowfield properties, such as density, velocity, temperature and pressure, and the other for plate surface properties, including pressure, shear stress, and heat flux. Those solutions are exact and validated by several sets of DSMC simulations as well.

Further based on the above solutions to free molecular jet impingement flow surface properties, various normalized coefficients [10][11][12][13] for the total jet loads over the plate surface can be integrated out accurately. Those loads include pressure and shear stress forces, torque, total heat flux, distances between plate center and various load centers (e.g., total pressure force, heat flux, toque) can be integrated out, and the evaluations are very convenient with a computer. No numerical simulations and measurements are needed any more. Hence, the work can significantly reduce investigation cost, e.g., computer resources, labor, materials and time. Even better, it turns out that we can use the above integrated total load coefficients at the free molecular flow limit, to estimate the corresponding coefficients for flows within the whole Knudsen number range. Different sets of DSMC simulations indicate that most of those coefficients [6][7][8][9] are insensitive to the Knudsen number. As such, those coefficients obtained at the free molecular flow limit [10][11][12][13] can offer anchoring values which are good approximates to start more accurate estimations.

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