行政院國家科學委員會專題研究計畫　成果報告

多稀薄超音速噴流與壁面間交互作用之研究(2/2)

計畫類別：個別型計畫
計畫編號：NSC91-2212-E-009-045-
執行期間：91 年 08 月 01 日至 92 年 07 月 31 日
執行單位：國立交通大學機械工程研究所

計畫主持人：吳宗信

報告類型：完整報告

處理方式：本計畫可公開查詢

中　華　民　國 92 年 12 月 9 日

行政院國家科學委員會補助專題研究計畫 x 成果報告 期中進度報告

多稀薄超音速噴流與壁面間的交互作用研究(2/2)
Interaction of Multiple Rarefied Under-expanded Supersonic Jets With Solid Walls (2/2)

計畫類別：X 個別型計畫 □ 整合型計畫
計畫編號：NSC91-2212-E-009-045
執行期間：91 年 8 月 1 日至 92 年 7 月 31 日

計畫主持人：吳宗信
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計畫參與人員： 周欣怡 曾坤樟

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中 華 民 國 92 年 10 月 20 日

行政院國家科學委員會專題研究計畫期末報告

多稀薄超音速噴流與壁面間的交互作用研究(2/2)
Interaction of Multiple Rarefied Under-expanded Supersonic Jets With Solid Walls (2/2)

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主持人：吳宗信* 國立交通大學機械工程學系

中文摘要

本計畫提議針對單一噴流、多噴流以及壁面的交互作用，以實驗及數值分析的方法做一詳細的探討與研究。本文章主要描述本計畫期末報告，包括：(1) 將單一或雙噴流之交互作用進行流場可視化 (2) 平行化三維非結構網格的蒙地卡羅直接模擬法（Direct Simulation Monte Carlo）模擬在不同的 Knudsen number 及不同壓力比下觀察噴流的結構變化

關鍵詞：平行化、非結構網格、蒙地卡羅直接模擬法、噴流、壓力比

Abstract

We have proposed to study experimentally and numerically the interaction of multiple rarefied under-expanded supersonic jets in the current two-year NSC-sponsored project. This report mainly describes the final results of the NSC project in two folds: (1) the flow fields of single or twin interacting parallel supersonic free jets are studied by flow visualization using laser-induced fluorescence of iodine molecules seeded in carrier Argon gas. (2) Supersonic jets issuing from a sonic orifice over a wide range of the stagnation Knudsen numbers, from a continuum to a near free molecular condition, and over a wide range of the pressure ratios are simulated by the parallel DSMC method.

Keywords: rarefied, under-expanded, supersonic jets, direct simulation Monte Carlo, pressure ratio

I. INTRODUCTION

Under-expanded supersonic jet has been studied extensively in the past due to its fruitful applications in rocket exhausts, fuel injectors, space-vehicle maneuvering thruster, aeroaccoustive and aerothermodynamic experiments [see Ref. 1 and the references cited therein]. The flow field includes fundamental gas dynamics from the continuum to the free molecular flow regimes [2]. At higher pressure levels, where a distinct shock system is formed, the jet structure is well understood [e.g., 3]. However, those at lower pressure levels, where the shock system is smeared and merged with the jet free boundaries, are not well studied [2].

Recently, there is an increasing interest to use the rarefied supersonic molecular beams (or under-expanded supersonic jet) as sources for thin film deposition in semiconductor industry [e.g., 4]. This process allows the heavier precursor molecules to be accelerated to a high kinetic energy (>1 eV), under which the reactive sticking coefficient of silicon hydrides increases substantially [4]. The use of seeding heavier precursor molecules into a lighter carrying gas jet offers better control of the incident kinetic energy of the reactant molecules striking the substrate. Striking molecular energy in the proximity of substrate plays an important role in controlling the film growth rate as well as the film growth quality. Hence, the understanding of the detailed flow field of the rarefied jet impingement and jet interaction becomes vital to improve the yield of thin film growth. In the past there were several studies concerning the details of the structure of a single jet [e.g., 5] and interaction between two jets [6] under rarefied conditions. However, the interaction between either single/multiple rarefied supersonic jets and interaction of the jets with the solid wall was rarely studied, where the configuration is important in practical applications of thin film deposition [4].

In the current study, we have proposed to study experimentally and numerically the interaction of single/multiple under-expanded supersonic jets with solid walls. To complete these goals experimentally, we have proposed to visualize the rarefied under-expanded jets using Laser Induced Fluorescence (LIF) generated by the iodine vapor seeding through the flow due to its simplicity and low cost of setting up the experiments. In addition, iodine vapor is only mildly poisonous. To facilitate this experiment, we have proposed to construct a vacuum chamber capable of maintaining the ambient pressure down to 0.01~1torr. In this report described in the following, the construction of the above-mentioned vacuum chamber has be completed, while the LIF experiments has finished in detail in the second year of the project.

In the past DSMC has been used to study the related problems concerning rarefied under-expanded supersonic jets and compared with experimental visualization wherever possible [e.g., 5-6]. These simulations, however, were problematic due to that the assumption of zero mean velocity at the outlet boundaries when computing the particle flux across the corresponding boundaries. In contrast, Wu and Tseng [7] have developed a method for processing pressure boundary conditions, which can be used for resolving this issue. In addition, at Gas Dynamics & Kinetics Laboratory (GDKL, http://taioan.me.nctu.edu.tw/~gdkl/) of National Chiao-Tung University, Our lab has successfully developed the DSMC method based on unstructured mesh and included the concepts as follows : Static Domain Decomposition, Mesh Refinement, Variable and Time Step Scheme and to apply. In the current study, we will use the parallel three-dimensional direct simulation Monte Carlo (DSMC) code to a parallel three-dimensional DSMC code as well as using a tetrahedral mesh.

The work in progress of the proposed research is, thus, summarized as follows:

1. To complete the simulation of single/twin under-expanded sonic jet issuing into a near-vacuum environment at different pressure ratios (stagnation/background), different upstream Knudsen numbers and different jet distances, and compare with experimental data whenever available.
2. To visualize the rarefied gas flow using LIF technique and observe interaction of single/twin rarefied under-expanded supersonic jets.

II. EXPERIMENTAL METHODS

Construction of the Vacuum Chamber

Figure1 shows a schematic sketch of the experimental apparatus used in this project. It consists of a high-pressure gas source (Ar), an iodine cell, a plenum chamber, a vacuum chamber, an orifice and a two-stage rotary pump. Pictures of the vacuum chamber and rotary pump are shown in Fig. 2. Carrier gas is supplied through a variable leak valve into the source chamber and mixed with sublimated iodine molecules. The mixture is expended through orifice (diameter D=0.5mm). Chamber pressure is expected to maintain at the level of 0.01~1 torr, which is well below the stagnation pressure in the plenum chamber (adjusted by the flow meter), to make the gas flow underexpanded at the exit of the orifice. Pressure ratio of plenum chamber to main chamber ranges 10~200. Gas temperature in the plenum chamber was measured by thermocouple (J-type). For flow visualization using LIF technique, laser light with wavelength of 532.5nm from Nd:Yag pulsed Laser was used to expand to a light sheet across the cross section of jet plume, which mixes with the Iodine vapor from Iodine cell. A CCD camera on the top of the main chamber will record the LIF image.

Instrumentation

The plume issuing from nozzle orifice should be imaged under different flow conditions. Images should be acquired in both normal and lateral directions. At this part of experiments iodine vapor should be seed in gas flow. Experiments using Nd-Yag laser as light source through light sheet optics to make a light sheet. The light sheet is then projected into the main chamber through the view-port. By adjusting the angle of light sheet optics we can acquire horizontal and vertical light sheets. After fluorescence phenomena occur, we take picture of plume issuing from orifice through a long pass filter (Oriel, Model No. 59510) from other view-port. When horizontal light sheet is applied, the image acquired is lateral cutting plane image. By adjusting the height of the light sheet we can get different lateral cutting plane images and finally combine the images by using computer. When vertical light sheet is applied, the image acquired is normal cutting plane image.

III. NUMERICAL METHODS

Extension of a Parallel Two-dimensional DSMC Code to a Parallel Three-dimensional DSMC Code

We have completed the extension of a parallel two-dimensional DSMC code to a parallel three-dimensional code. Main features of this newly completed DSMC code include capability of handling unstructured tetrahedral mesh, portable parallel paradigm on memory-distributed machines (Message Passing Interface, MPI), static domain decomposition, variable time scheme and mesh refinement. Reason for using variable time-step scheme is to have a good computational efficiency and more uniform particle distribution. In addition, mesh adaptation in DSMC can result in better flow resolution, especially when the flow involves shock-wave structures.

Results for a Single and Twin Jets

We have used this parallel three-dimensional DSMC code to simulate a single and two jets issuing from orifice(s). It is assumed that Mach number of unity is reached at the exit of the orifice plate, which of course requires future study due to viscous effects. Flows are simulated at the conditions of Knudsen numbers of both 0.1 and 0.001 for single and multiple jets, respectively and pressure ratio (P_s/ P_b) from 50 to ∞. Knudsen number is defined as the ratio of mean free path in the reservoir to the orifice diameter. P_s is stagnation pressure (upstream pressure) and P_b is background pressure (downstream pressure).These two Knudsen numbers represent the extreme cases in the transitional flow and the near-continuum flow, respectively. Approximately 30,000~1,050,000 tetrahedral cells and 350,000~3,300,000 particles are used for the DSMC simulation, depending on the flow conditions.

Normalized density distribution of a single jet issuing from a single orifice are illustrated in Fig. 3 and Fig. 4 for Knudsen numbers equal to 0.1 and 0.001and pressure ratios equal to 0 and ∞, respectively. Results show that a clear barrel-type shock clearly formed in the near field of the orifice exit for Kn=0.001 when pressure ratio is less than P_s/P_{b}=50, while no shock is formed for Kn=0.1due to strong rarefaction. Typical LIF images are presented in Fig. 5 and Fig. 6 for Kn=0.0005 and Kn=0.017, respectively.

Normalized density distributions of two jets issuing for Knudsen number equal to 0.001and 0.1 respectively under L/D=3 and 6 are illustrated in Fig. 7 and 8, respectively. Similar flow fields are found for each jet as the single jet, while strong interaction between two jets occurs at some closer distance between the orifices exits is clear. LIF visualization results are also presented in Fig. 9 and Fig. 10, respectively, under the same situation of simulation.

IV. CONCLUSIONS

In the current project, single and multiple jet interactions are studied using LIF visualization and DSMC simulation at different flow conditions. Results show that the flow structured are rather complicated and the comparison between experimental visualization and DSMC simulation are compatible.

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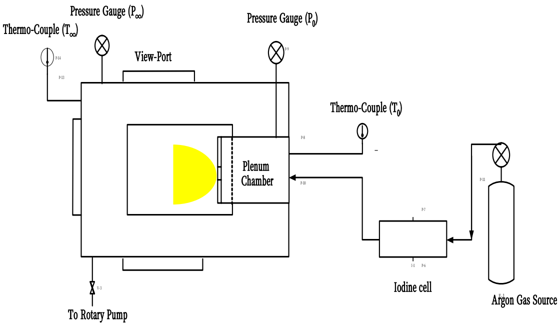
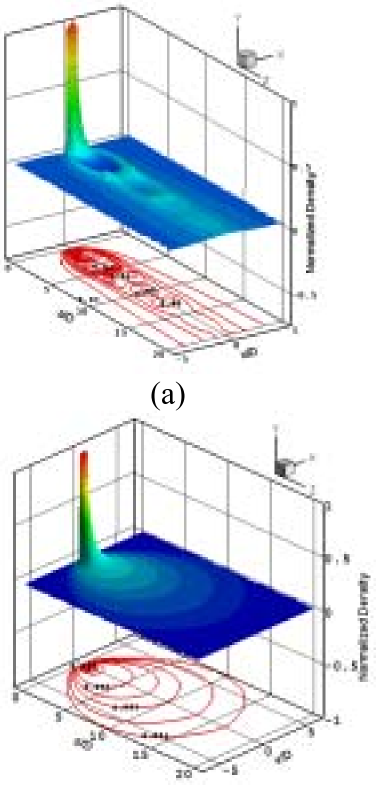


Fig. 1 Sketch of the experimental apparatus

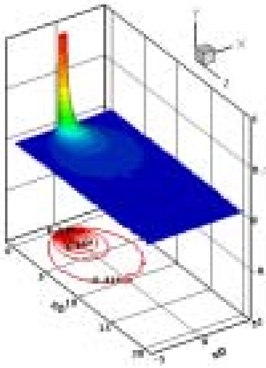
Fig. 2 Pictured of vacuum chamber (a) Small Vacuum Chamber (90mm x 90 mm x 200mm)



(a)

(b)

Fig. 3 Normalized density distribution for a single jet (a) Kn=0.001,Ps/Pb=50; (b) Kn=0.001,Ps/Pb=∞ .



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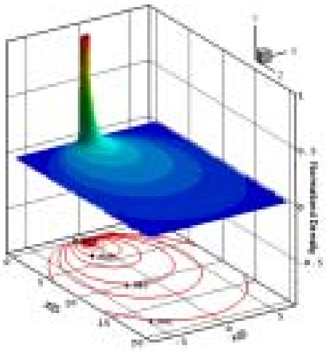
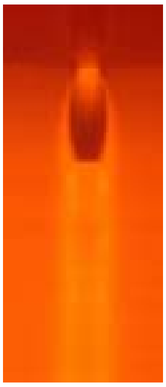
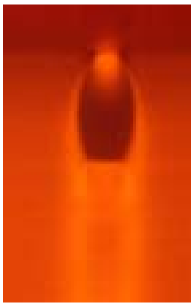


(b)

Fig. 4 Normalized density distribution for a single jet (a) Kn=0.1,Ps/Pb=50; (b) Kn=0.1,Ps/Pb=∞ .

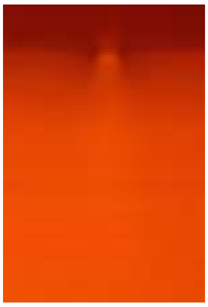


(a)



(b)

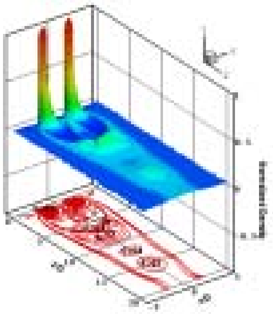
Fig. 5 LIF result for a single jet (a) Kn=0.0005,Ps/Pb=50; (b) Kn=0.0005,Ps/Pb=100.



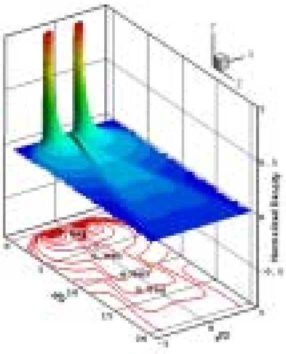
(a)

(b)

Fig. 6 LIF result for a single jet (a) Kn=0.0017,Ps/Pb=100;(b)Kn=0.0017, Ps/Pb=245.

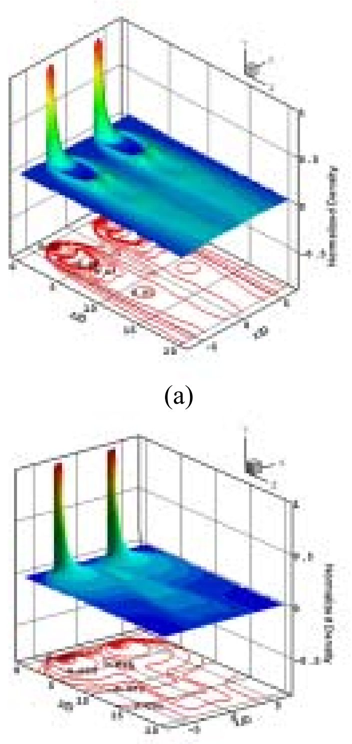


(a)



(b)

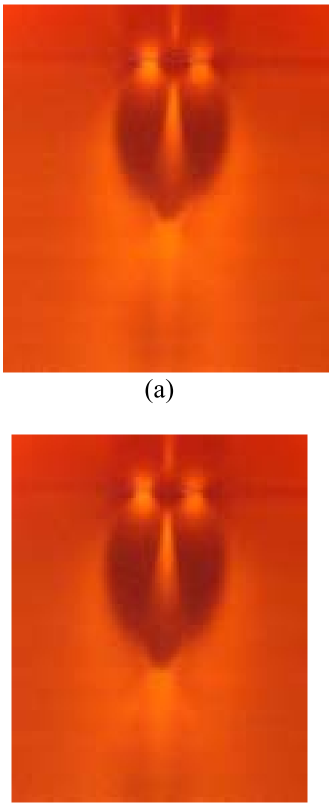
Fig. 7 Normalized density distribution for two jets of L/D=3 (a) Kn=0.001,Ps/Pb=50; (b) Kn=0.1, Ps/Pb=50



(a)

(b)

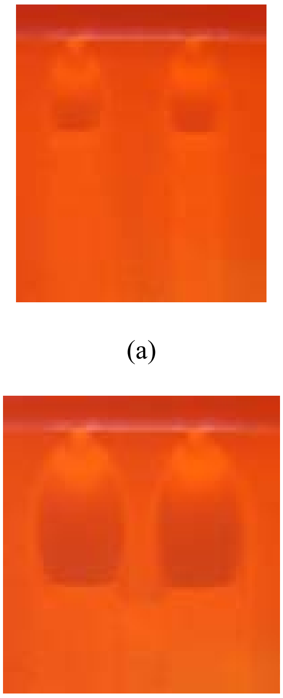
Fig. 8 Normalized density distribution for two jets of L/D=6 (a)Kn=0.001,Ps/Pb=50; (b) Kn=0.1, Ps/Pb=50



(a)

(b)

Fig. 9 LIF result for two jets of L/D=3 (a) Kn=0.01,Ps/Pb=200; (b)Kn=0.001, Ps/Pb=267.



(a)

(b)

Fig. 10 LIF result for two jets of L/D=6 (a) Kn=0.0001,Ps/Pb=200;(b)Kn=0.0017, Ps/Pb=320.