Flow Field Analysis of Jet Impinging on an Inclined Flat Plate at High Plate Angles

Masato Ito[*]
Aoyama Gakuin University, Sagamihara, Kanagawa, 229-0006, Japan

Akira Oyama[‡] and Kozo Fujii[§]
JAXA/ISAS, Sagamihara, Kanagawa, 229-8510, Japan

and

A. Koichi Hayashi[†]
Aoyama Gakuin University, Sagamihara, Kanagawa, 229-0006, Japan

Flow fields of the supersonic jets impinging on an inclined flat plate at high plate-angles are experimentally investigated using surface pressure measurement with pressure sensitive paint and Schlieren flow visualization. While Type I flow type is dominant at high plate angles, the present research found a new flow type "TYPE I with bubble" at plate angle between 60 and 80 degrees. The flow classification according to L/L_s' and plate angle indicated that the constant x/L'_s curve doesn't represent the boundary of Type I and Type II anymore at high plate angles between 60 and 90 probably because Type II flows at low plate angles and high plate angles is different phenomena. This study also indicates that the curve dividing Type I and Type I with bubble regions is same as the curve dividing Type II and Type II with bubble regions.

Nomenclature

D_n	=	nozzle exit diameter
L	=	nozzle-plate distance
L'_s	=	distance from the nozzle exit to the location at the maximum diameter of the Barrel shock structure
P	=	pressure
P_c	=	total pressure
PR	=	pressure ratio; the nozzle exit static pressure to ambient pressure
x	=	distance from the nozzle lip to the point that the jet boundary first impinges on the plate
θ	=	inclined angle of plate (90 degrees mean perpendicular location against the jet flow)

[*]Graduate Student, Department of Science and Engineering, 5-10-1Fuchinobe, Student Member AIAA.
[‡]Research Associate, Department of Space Transportation Engineering, 3-1-1 Yoshinodai, Member AIAA.
[§]Professor, Department of Space Transportation Engineering, 3-1-1 Yoshinodai, Fellow AIAA.
[†]Professor, Department of Science and Engineering, 5-10-1Fuchinobe, Member AIAA.

I. Introduction

FLOW fields created by supersonic jets impinging on an inclined flat plate appear in a variety of industrial applications. Examples in aerospace industry can be found in vertical takeoff and landing engineering, plume-wall interactions during multi-stage rocket separation in high attitude, space module attitude-control thruster operation, deep space docking of satellites and many more. Generally, these flows are extremely complex due to mixed subsonic and supersonic regions, interacting shock and expansion waves and strong shear layers.

There can be found a number of papers in this research field[1-3] and understanding of the flow fields is gradually increasing. However, most of traditional approaches use array of pressure taps for surface pressure measurement over a plate and thus the previous discussions based on such limited point-wise information under limited flow conditions especially under high-pressure ratios for the supersonic jet impingement. Therefore, the detail of the flow structure at various conditions was not revealed.

Recently, new techniques of surface pressure or temperature measurement system called Pressure/Temperature Sensitive Paint [PSP/TSP] are often used among the field of aerospace[4-6]. Nakai *et al.*[7] proposed use of PSP for measurement of the surface pressure on the plate. PSP bases on the oxygen quenching of the photoluminescence and can easily obtain the surface pressure distribution as an image with much higher spatial resolution compared to the conventional point-wise measuring system such as pressure taps.

In the research by Nakai *et al.*, flow fields of the jet impinging on an inclined flat plate at various plate angles, pressure ratio, and nozzle-plate distance are observed by the PSP surface pressure measurement and the Schlieren method. From the experiments, they found that the flow patterns can be classified into three types and the flow types can be easily predicted when the flat plate angle, nozzle plate distance and shock cell length are known in advance. However, their observation is limited to plate angles between 30 to 60 degrees (90 degrees mean perpendicular location against the jet flow) and flow field of the jet impinging on the plate at high plate angle, which is of great importance in engineering view point, was not investigated.

Therefore, objective of the present study is to investigate the flow structure created by the jet impingement at high flat plate angles (60 to 90 degrees) using the PSP measurement and the Schlieren method. Rest of the paper is organized as follows: Section II introduces the flow type classification by Nakai et al. Section III explains the present PSP-based measuring system. Section IV discusses results of the present experiments. Section V concludes the present work.

II. Flow Type Classification at Plate Angle between 30 and 60 Degrees by Nakai *et al.*

In the reference[7], the flow structure created by a jet impingement at flat plate angles θ between 30 and 60 degrees, nozzle-plate distance L/D_n between 1 to 4.5, and pressure ratio PR between 4.5 and 10.1 are carefully observed and classified into three types (Fig. 1) based on the observation of the Schlieren images and the pressure distributions over the plate measured by PSP.

Nakai *et al.* found that the parameters that define the flow type are L/L_s' and θ. They also found the flow types are classified by the curve that x/D_n is constant and whether or not the stagnation bubble appears can be predicted with the angle between the upper jet boundary and the plate (Fig.2).

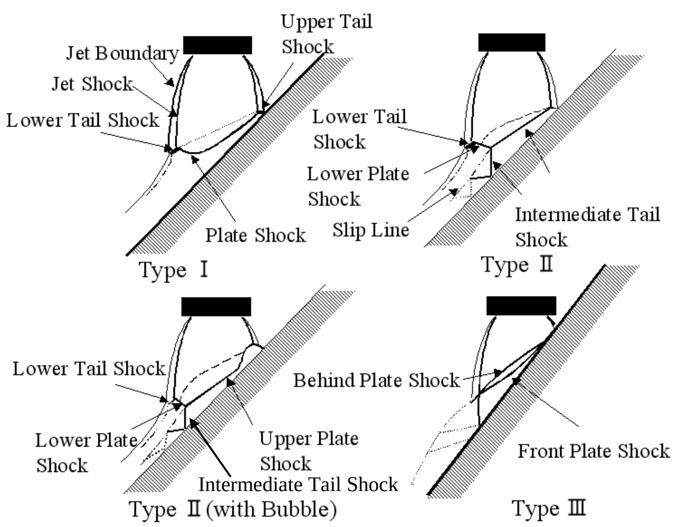


Figure 1. Schematic pictures of typical flow structure.

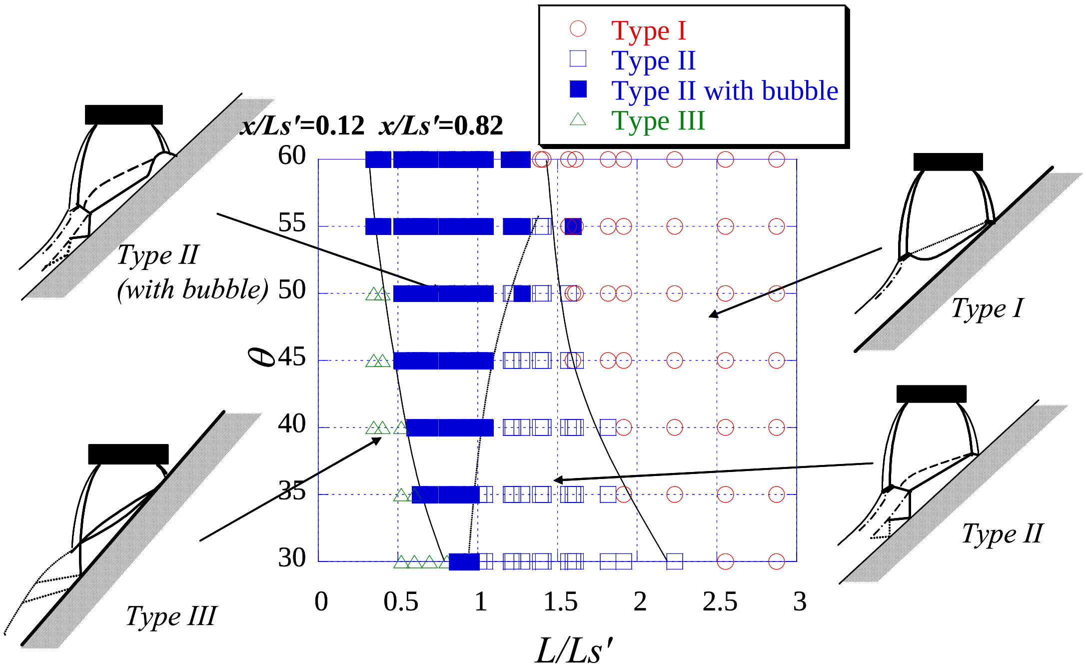


Figure 2. Classification of the flow patterns ($30 \le \theta \le 60$).

III. Experimental Setup

Experiments of the jet impingement at high flat plate angles are carried out in the same induction-type wind tunnel used in the research by Nakai *et al.*[7] The test section is connected to a large low-pressure chamber and dried air is sucked into the test section (Fig.3). The total pressure of the nozzle flow is kept constant and the ambient pressure near the flat plate is varied for the proper set-up of the pressure ratio of the nozzle exit and the ambient pressures. The conical nozzle with a design Mach number of 2.2 is connected to the settling chamber where the pressure is kept to be 100[kPa]. A flat plate is placed in the test section and is located on the electrically controlled stage. Location and angle of the flat plate are changed for the range of L/D_n from 1.0 to 4.5 and θ from 60 to 90 degrees.

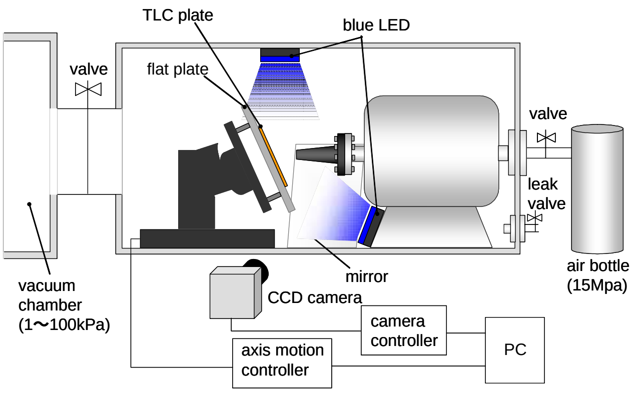


Figure 3. Schematics of the test section and measurement system.

For PSP/TSP measurement, blue LED arrays are used as excitation light sources. Ru(phen) [Dichlorotris (1,10-phenanthroline) ruthenium (II)] and acryl resin [Hobby Color: GSI Creos] are used as the luminophore and the binder, respectively. The CCD camera used to capture the luminescence of PSP/TSP has 1024×1024 pixels resolution and 12bit intensity resolution. A 650±20nm band-pass filter is placed in front of the camera object lens to separate the paint emission from the excitation light. Because of test section's space limitation, LED is placed in the test section and the luminescence of PSP/TSP reflected by a mirror is captured by the CCD digital camera placed outside through the observation window. Accuracy of the current PSP measurement system has been validated in the reference[7].

In addition to the measurement over the plate surface, flow visualization with the Schlieren system is carried out to obtain images of the cross section of the flow fields.

IV. Results and Discussions

(1) Effect of the nozzle-plate distances

The surface pressure maps on the plate, the pressure distribution plots along the centerline, and the Schlieren images at θ of 70 degrees, *PR* of 4.5, and L/D_n between 1.0 and 4.0 are presented in Fig. 4.

At L/D_n of 1.0, intermediate tail shock and corresponding pressure peak (peak C) is observed in the Schlieren image and the pressure plot, respectively. In addition, the stagnation bubble is recognized in the Schlieren image while the corresponding pressure peak is not recognizable in the pressure plot as the pressure peak due to the plate shock (peak A) is dominant. Thus, this flow is judged as TYPE II with bubble.

The flow fields at the nozzle-plate distance of 2.0 and 3.0 are categorized as TYPE I flow type because they have the plate shock and upper and lower tail shocks while they don't have the intermediate tail shock as seen in the Schlieren images. The Schlieren images also indicate that these flows have stagnation bubble upstream of the pressure peak A as shown in the white circles. The pressure plateau due to the bubble is also observed in the pressure distribution (region D). It is interesting that TYPE I flow can have stagnation bubble at high plate angle while it never has any stagnation bubble at plate angle between 30 and 60 degrees.

At L/D_n=4.0, the flow is classified as TYPE I flow but the stagnation bubble disappeared. It seems that the stagnation bubble disappears when the pressure peak A due to the plate shock becomes small.

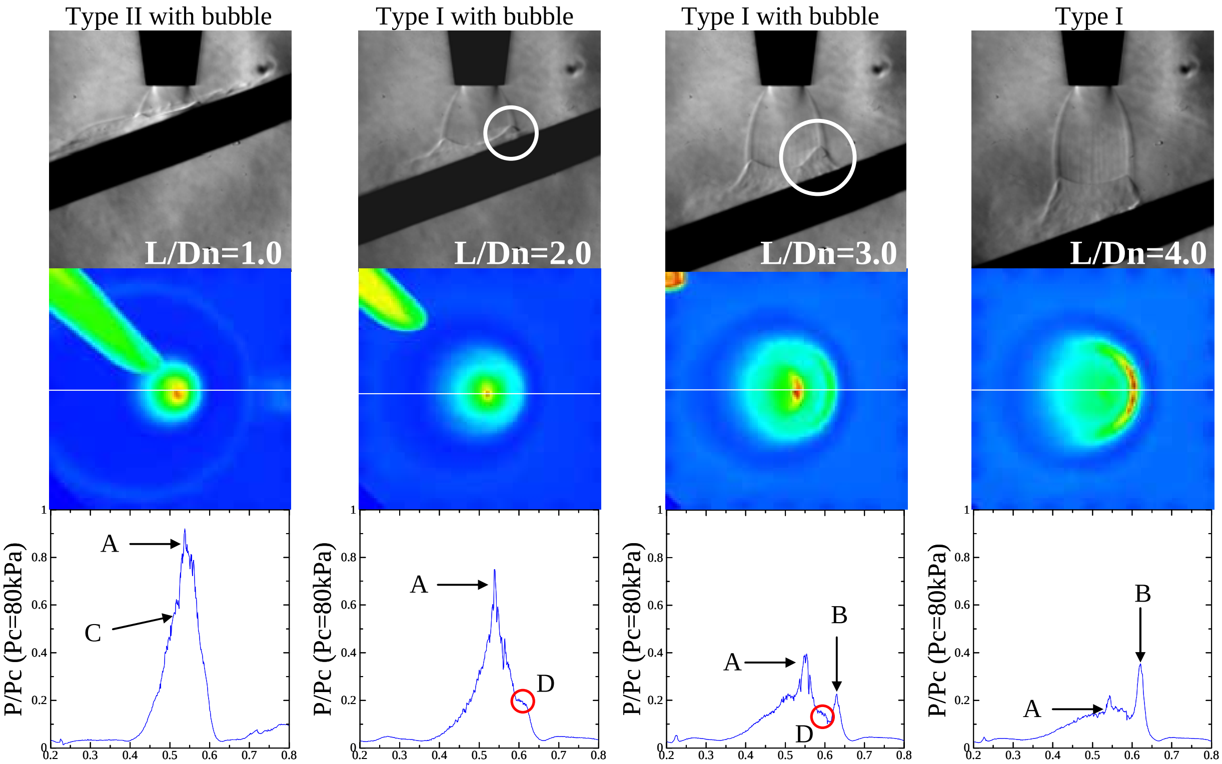


Figure 4. Schlieren images, pressure maps, and pressure plots under various nozzle-plate distances at θ of 70 degrees are presented at *PR* of 4.5

(2) Effect of the plate angle

The surface pressure maps on the plate, the pressure distribution plots along the centerline, and the Schlieren images at L/D_n of 2.0 are presented at *PR* of 4.5 and θ between 60 and 90 degrees (Fig. 5).

At θ=60 degrees, the flow type is judged as Type II with bubble because the intermediate tail shock and the stagnation bubble are recognized in the Schlieren image and the corresponding pressure peak and plateau are observed in the pressure plot (peak C and region D).

As seen in the previous section, the flow at θ=70 degrees can be judged as TYPE I with bubble. At high plate angles, the strong plate shock reduces speed of the main stream from supersonic to subsonic. As a result, the intermediate shock waves are not generated.

At θ of 80 and 90 degrees, the flow remains TYPE I with bubble where the pressure plateau due to the stagnation bubble is observed in the pressure distributions. However, as the plate angle becomes higher and the nozzle-to-plate distance becomes shorter, it becomes more difficult to judge whether or not the stagnation bubble exist from the Schlieren images.

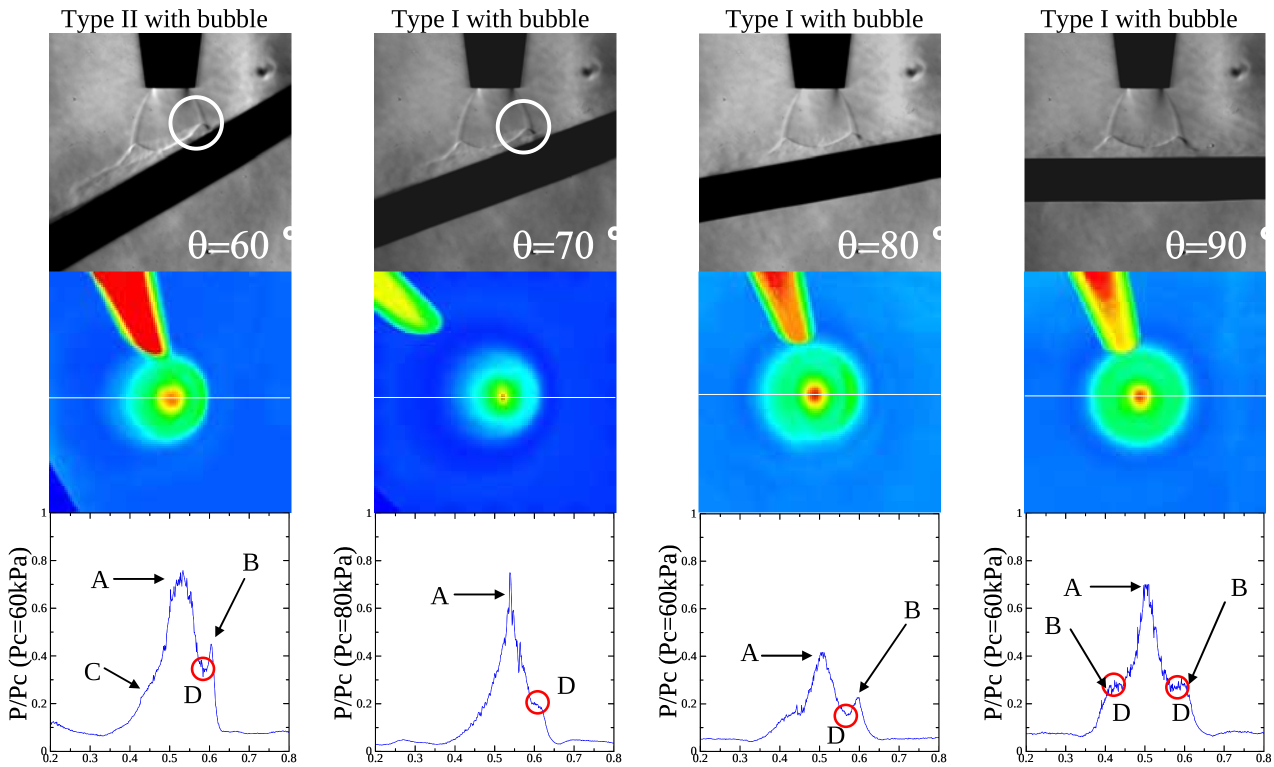


Figure 5. Schlieren images, pressure maps, and pressure plots under various plate angles at *L/Dn* of 2.0 degrees are presented at *PR* of 4.5

(3) The flow classification

Figure 6 is the present result of classification of the flow patterns at plate angle θ between 60 and 90 degrees with the flow classification by Nakai *et al.* at plate angle between 30 and 60 degrees. At high plate angles (between 60 and 90 degrees), Type I with bubble flow type is dominant at high plate angles because the strong plate shock reduces the speed of main stream to subsonic at low plate angles.

Figure 7 plots the flow classifications at different pressure ratios according to the parameter L/Ls' instead of L/D_n . This figure shows that influence of the pressure ratio can be removed even at high plate angles.

An interesting point is that the constant x/L'_s curve that divides the Type I and Type II regions at plate angle between 30 and 60 degrees doesn't represent the boundary of Type I and Type II anymore at plate angle between 60 and 90 degrees. Thus, different phenomena may change the flow from Type I to Type II flows at low and high plate angles. At high plate angles and low L/L_s', it is likely that the flow becomes TYPE II when the decelerated flow due to the strong plate shock perpendicular to the jet is accelerated by high stagnation pressure to produce the intermediate shocks while at low plate angles, the flow becomes TYPE II because deceleration due to the plate shock oblique to the jet is not enough for the flow to be subsonic.

Figure 7 also indicates that the curve dividing Type I and Type I with bubble regions is same as the curve dividing Type II and Type II with bubble regions. Thus, whether or not the stagnation bubble appears is determined by the angle between the upper jet boundary and the plate as the low plate angle conditions.

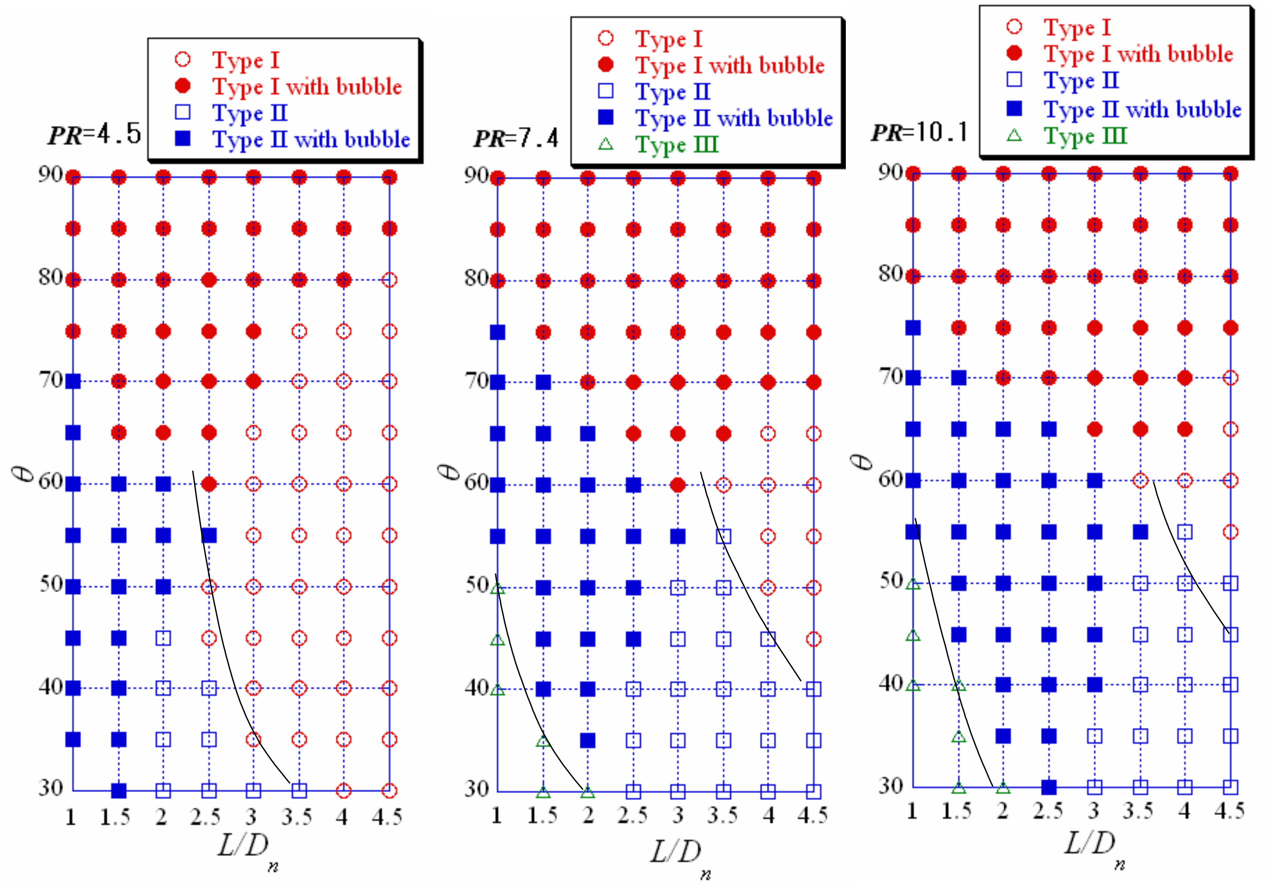
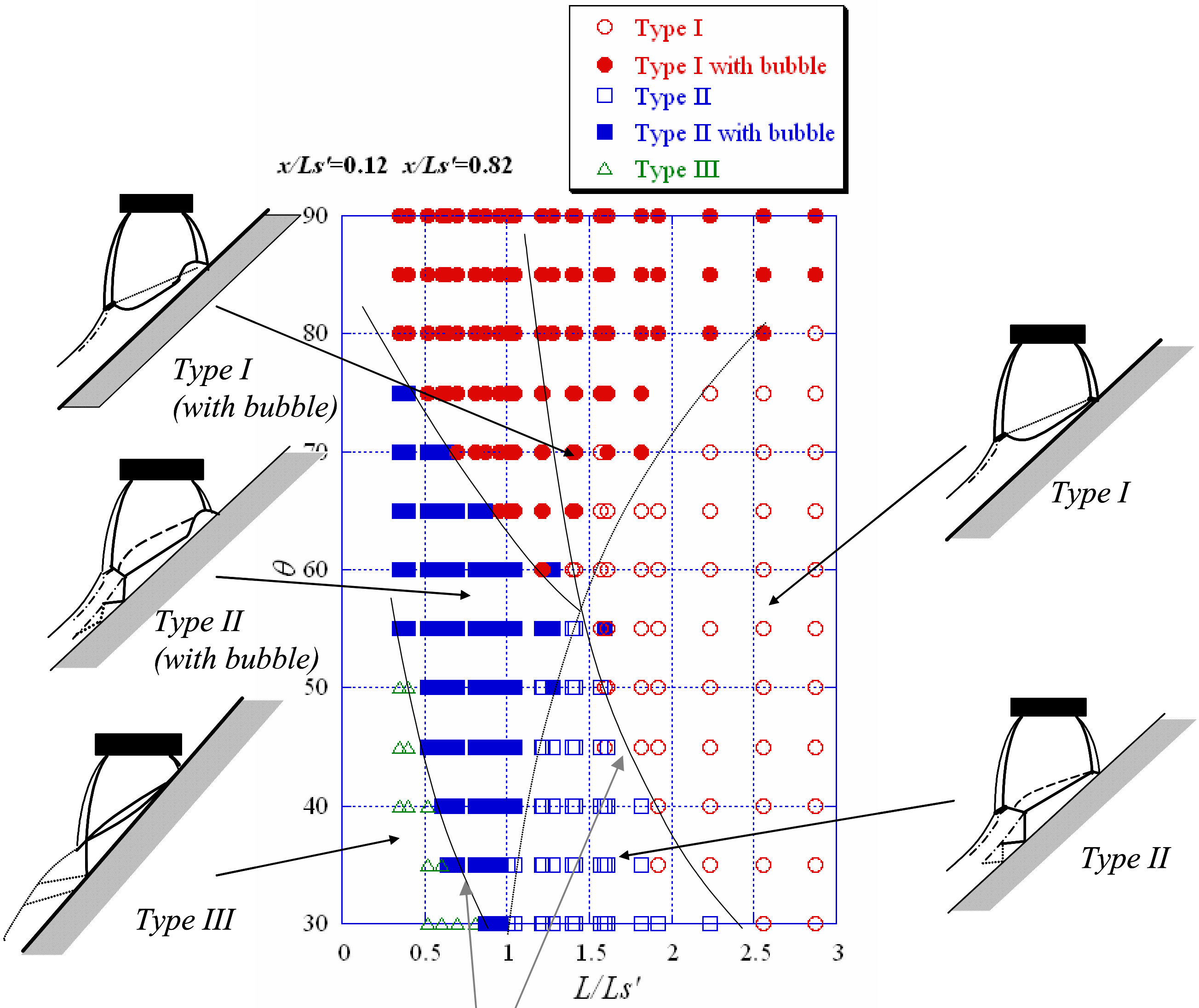


Figure 6. Classification of the flow patterns.



$$\theta = \tan^{-1}\left(\frac{r/Ls'}{(L/Ls')-(x/Ls')}\right)$$

Figure 7. Classification of the flow patterns.

V. Conclusions

Flow fields of the supersonic jets impinging on an inclined flat plate at high plate-angles has been experimentally investigated using surface pressure measurement with pressure sensitive paint and Schlieren flow visualization. Because the plate shock perpendicular to the jet flow decelerates the flow to subsonic at high plate angle conditions, Type I flow type was dominant at high plate angles. The present research found a new flow type "TYPE I with bubble" at high plate angles.

The flow classification according to L/L_s' and plate angle indicated that the constant x/L'_s curve doesn't represent the boundary of Type I and Type II anymore at high plate angles between 60 and 90. The Type II flows at low plate angles and high plate angles may be different phenomena. Further experiments as well as computational analysis will be conducted to identify the potential parameters defining the flow structure at high plate angle. This study also indicates that the curve dividing Type I and Type I with bubble regions is same as the curve dividing Type II and Type II with bubble regions. Thus, whether or not the stagnation bubble appears is determined by the angle between the upper jet boundary and the plate as the low plate angle conditions.

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