TECHNICAL NOTE

INVESTIGATION OF CLOUD FORMATION OVER PSLV HEATSHIELD

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Abstract

Cloud formation was seen around the heatshield region in the transonic and low supersonic Mach number regime of PSLV flight. It is observed that the cloud formation is due to local condensation of moisture in the ambient air due to expansion of air around the heatshield and corresponding reduction in the local temperature over the heatshield in the transonic and low supersonic regime. CFD studies in conjunction with atmospheric dew point variation and flight trajectory data indicate the possibility of cloud formation around PSLV heatshield in the transonic and low supersonic regime. This type of condensation cloud in the transonic regime is known as "Prandtl-Glauert (PG) Cloud" and the condensation is also observed in the low supersonic Mach numbers. The condensation cloud formations are also observed over air-crafts.

Nomenclature

c_p = specific heat at constant pressure
M = Mach number
p_s = saturated vapour pressure, pa
p_v = vapour pressure, pa
p = pressure, pa
S = saturation factor
T = temperature, K
u = velocity, m/s

Greek Symbol

γ = ratio of specific heat

Subscript

∞ = freestream

Introduction

Successful launch of Polar Satellite Launch Vehicle (PSLV) took place on 05.05.2005 from Satish Dhawan Space Centre, SHAR, India. Intermittent cloud formation on the heat shield was observed during the initial ascent phase of launch. Fig.1 shows the snap shots from the video footage, showing intermittent cloud formation, which took place during a time frame of ~26 to 42 seconds from the vehicle lift-off. From the trajectory details this time period corresponds to the transonic and low supersonic regime of flight.

Natural flow visualization occurs when the water vapour contained in the ambient air is condensed due to local low pressure and the related low temperature of the air. If the ambient air is sufficiently humid, the drop in the temperature is enough to place the water vapour in the two-phase regime resulting in the formation of condensation cloud. The condensation cloud is a visible mass of condensed water droplets or ice crystals suspended in the atmosphere. The water droplets when surrounded with billions of other droplets or crystals, are visible as clouds.

Natural condensation has been observed in the aircrafts in flight [1] and it usually occurs without any warning, since, the condensation is very sensitive to the atmospheric weather and flight conditions. Condensation also occurs in high speed wind tunnels, when the stream temperature drops below the dewpoint temperature [1]. Experimental and numerical studies on the nozzle condensation have been reported [2-4]. Numerical simulations based on classical nucleation theory [5],[6], transonic small disturbance theory [7] and experimental studies [8] on condensation over airfoils have been carried out to study the effect of condensation on the aerodynamic behaviour.

In this present investigation on cloud formation over PSLV, Computational Fluid Dynamic (CFD) studies in conjunction with the trajectory and dew point details reveal the possibility of condensation cloud formation over PSLV heat shield during the transonic and low supersonic

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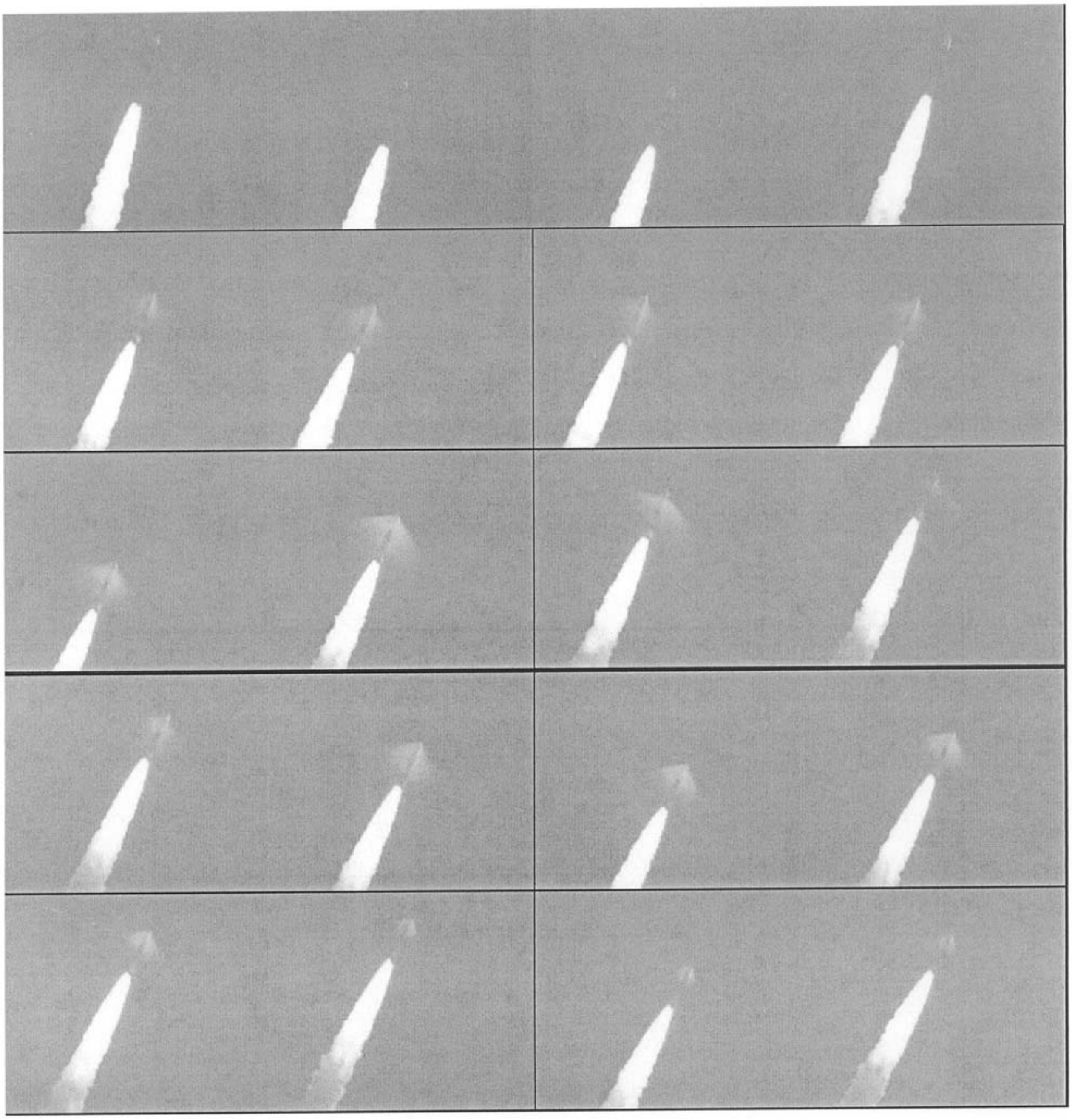

Fig.1 Frames showing condensation cloud over PSLV heat shield in the transonic and low supersonic regime

regimes of flight. The details of these studies are reported in this paper.

Condensation Phenomenon

High speed transonic and supersonic flow over aircraft canopy, wing and cone-cylinder junction of launch vehicles results in a supersonic expansion. The flow expansion results in reduced pressure and temperature satisfying the isentropic relationship, Eq.(1).

$$T \propto P^{(\gamma - 1)/\gamma} \tag{1}$$

In the transonic flows when the local Mach number due to expansion approaches the ambient speed of sound, the perturbation in pressure and temperature theoretically approaches $\pm\infty$. This situation is expressed by the function in Eq.(2).

$$\frac{T - T_\infty}{u^2/2c_p} = \frac{Constant}{\sqrt{1 - M_\infty^2}} \tag{2}$$

Where the constant in Eq.(2) depends on the specific shape and orientation of the wing or body, but not on the Mach number or aircraft speed. Equation (2) holds for gases at atmospheric pressure. The term $|1 - (M_\infty)^2|^{1/2}$ seen in Eq.(2) will be very small when the flight Mach number M_∞ is near one. As a result, the right hand side of Eq.(2) will be very large when $M_\infty \approx 1$ and the temperature perturbation $(T - T_\infty)$ will be correspondingly large. This amplification is referred to as the *"Prandtl-Glauert (PG) Singularity"*.

When the temperature of gas mixture with condensable components drops below the dewpoint temperature of the mixture, phase transition can occur [9]. Generally, when the phase transition occurs, it is observed that the state of phases is in equilibrium. In supersonic expansion flows, due to rapid change in the conditions, the phase changes do not take place at equilibrium conditions but at rather large departures from these conditions [3],[9]. The saturation factor S indicates the departure from equilibrium conditions. For calorically perfect gas, S is defined as the ratio of the vapour pressure p_v and the saturation pressure p_s at local temperature T, Eq.(3).

$$S = \frac{p_v}{p_s(T)} \tag{3}$$

A saturation factor of unity ($S = 1$) refers to an equilibrium situation. In the vapour-pressure temperature state diagram in Fig.2, this is indicated as the liquid vapour coexistence curve [1]. When, the saturation factor $S \geq 1$ results in likely onset of condensation and for an already existing condensate, a saturation factor of $S \leq 1$ results in likely onset of evaporation. During the isentropic expansion of flow, the conditions may change to a state in the liquid region in Fig.2, without condensation taking place. This situation corresponds to a saturation factor having a value higher than unity, and the mixture is called supersaturated or super cooled. At some point in the super cooled state, where S can be very high, the relaxation to the equilibrium state is initiated by homogeneous nucleation by formation of stable clusters of vapour molecules. The rate at which these clusters are formed is called the homogeneous nucleation rate '*J*'. These clusters grow and deplete the vapour and release the latent heat, which increases the temperature and thereby reduces the saturation factor to unity and hence results in the end of condensation process.

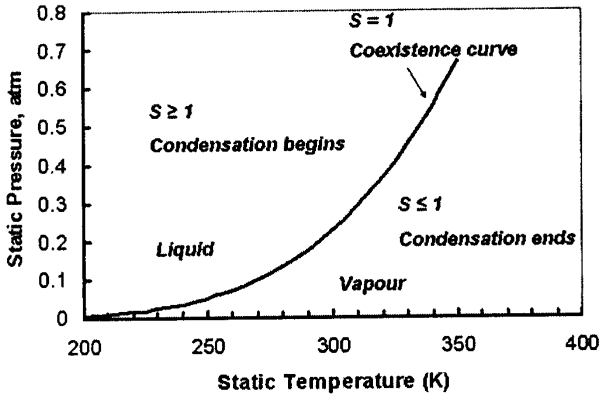

Fig.2 Saturated vapour-pressure curve for water

In supersonic expansion flows in nozzle, the process of homogeneous nucleation is prevalent over heterogeneous nucleation (foreign particles acting as nuclei).The rapid time scale of the nozzle flow results in homogeneous nucleation, even though, the typical number of dust particles in air that can act as nuclei is about 10^{10} m^{-3}.

Cloud Formation Over Aircrafts and Launch Vehicles

In general, condensation occurs during aircraft landing, take-off and during the transonic flight of aircraft and launch vehicles. Condensation over the wing of aircraft during take-off and landing is due to the expansion of air on the leeward side of wing due to lift, which leads to local condensation known as *"Lift Induced Condensation[10]"*.

Figure 3 shows the Space Shuttle during landing [10], where the condensation occurs on the wing leeward side, due to suction pressure created by the leading edge vortical flow. Due to the reduction in pressure a corresponding reduction in temperature results in the condensation of water vapour on the upper surface of the wing. A characteristic feature of lift-induced condensation is that it is asymmetric, i.e., there will be much more condensation on the upper side of the wing than on the lower side. The condensation is also taking place along the wing tip vortices.

Fig.3 Condensation during space shuttle landing

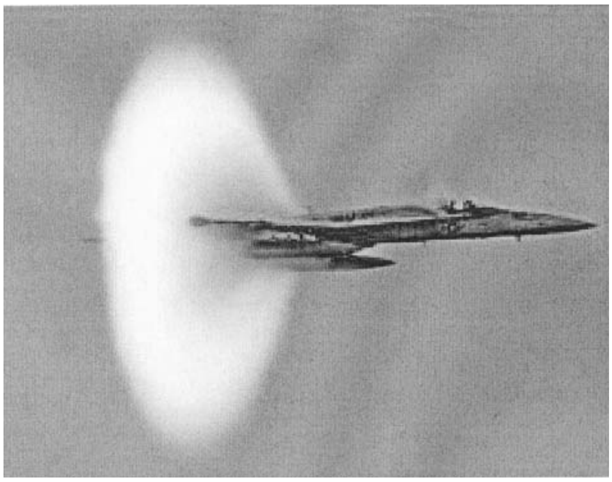

Fig.4 F-18A condensation cloud near M = 1

Figure 4 shows the conical-shaped condensation cloud over F18A aircraft [11] as it accelerates through the sonic barrier. The freestream flow accelerates to supersonic speeds above and below the wing, causing the flow to condense in the expansion waves in the front portion of the condensation pattern. The aft end of the pattern is created by a shock wave through which the flow is decelerated back to subsonic speeds and rapid temperature rise through the shock causes the condensed flow to evaporate. The condensation cloud is also seen on the canopy. If the Mach number is sufficiently close to one, the temperature perturbations in the low-pressure, low-temperature portions of the flow can become large enough to cause condensation of the ambient water vapour, and it is referred as *"Prandtl-Glauert (PG) condensation cloud [11]"*.

Dew Point and Humidity

Dew point is the temperature to which, volume of air would have to be cooled without changing its pressure or moisture content in order to condense some of vapour in to tiny droplets, that is, to initiate the formation of fog. The amount of water vapour in the air at any given time is usually less than that required to saturate the air. The relative humidity is the percentage of saturation humidity. Eq.(3) is the saturation factor is also known as relative humidity, and it is generally calculated in relation to the saturated vapour pressure.

For example, let the actual vapour density is 10 gm/m^3 at 20°C compared to saturation vapour density of 17.3 gm/m^3 at that temperature and if the local temperature decreases to a point, where the saturation vapour density is 10 gm/m^3, i.e., the relative humidity is 100%, then this temperature in other word is known as dew point. When the temperature and dew point are equal, the relative humidity is 100%. Thus, dew point never exceeds the local temperature.

PSLV Cloud Studies

The condensation phenomenon is studied in Ref. [1] by the post processing the CFD data, (which does not incorporate any condensation model) to compute the local relative humidity, which is a strong function of local temperature and a qualitative indicator of the condensation process. Local relative humidity is computed as a function of free stream relative humidity, local free stream static pressure and temperature. The freestream relative humidity of 0.85 is assumed for all the computation, whereas the local temperature and pressure are computed from CFD simulations.

In the present investigation of cloud formation over PSLV heatshield, a similar post processing of the CFD data was carried out, but with direct information of atmospheric dew point variation over the launch site. The trajectory data are used as inputs for the CFD simulations.

Flight Trajectory Details

Figure 5 shows the initial trajectory data, i.e., Mach number and altitude verses time plot. The data is shown for a time frame of 20 to 50 seconds from lift-off. The condensation phenomenon took place between ~26 - 42 seconds and the corresponding Mach number ranged from 0.77 (2.8 km) to 1.61 (8.44 km). These details are given as input for the CFD simulations.

Dew Point Variation

One of the important inputs to the present investigation is the *dew point* variation with altitude on the day of launch on 05.05.2005. Fig.6 shows the dew point variation and ambient temperature distribution with altitude at Satish Dhawan Space Centre, SHAR, India.

CFD Simulation

The CFD simulations were carried out using in-house PARAS3D CFD solver [12]. The code is based on finite volume formulation and uses Riemann solver for inviscid flux computation and a modified wall function approach for modeling the viscous flow near the wall. The solver can run on serial or in parallel computing mode. Cartesian grids can be automatically generated over any arbitrary bodies using the pre-processor in a short time. Navier-Stokes solver with k-epsilon turbulence model and Euler solver are available for flow simulation. The grids can be refined during the solution procedure.

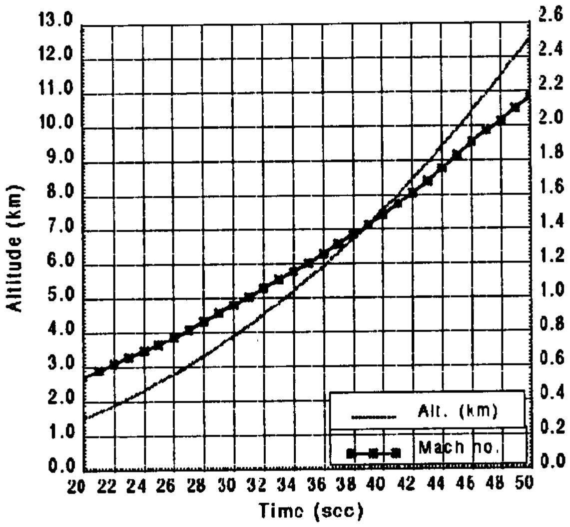

Fig.5 Initial - flight trajectory details

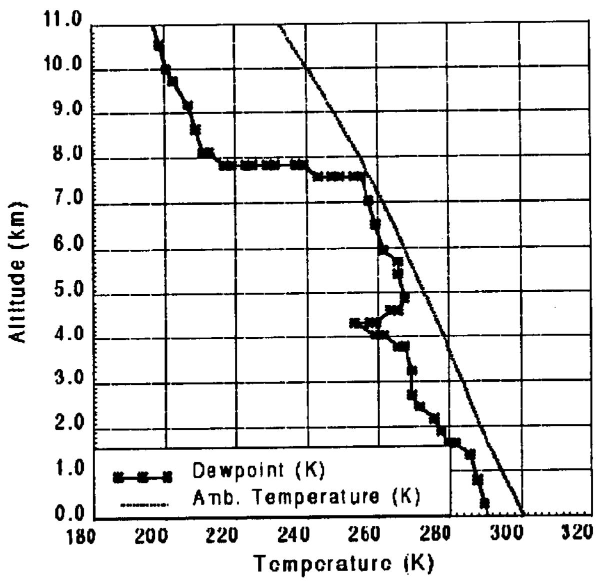

Fig.6 Dew point variation at SHAR on 05.05.05

In the present study, CFD simulations were carried out using Euler solver at zero angle of attack and at different Mach numbers corresponding to the trajectory; the details are given in Table-1. Cartesian grid was generated over the heat shield region of PSLV configuration. The idea of carrying out Euler simulation is to get qualitative details on cloud formation phenomenon. The flow field analysis was carried out using the temperature distribution around heatshield portion, where the maximum temperature limit is given as the dew point at the corresponding altitude.

Table-1 : CFD simulations

Sl. No.	Time (sec)	Alt (Km)	M	T (K)	Dewpoint (K)
1	26.0	2.80	0.77	284.60	269.47
2	26.5	2.92	0.79	283.98	269.47
3	27.0	3.05	0.82	283.30	269.47
4	27.5	3.18	0.84	282.66	269.47
5	28.0	3.32	0.86	281.94	269.18
6	28.5	3.46	0.89	281.21	268.65
7	29.0	3.60	0.91	280.50	268.13
8	29.5	3.75	0.94	279.70	267.57
9	30.0	3.89	0.96	278.97	265.06
10	31.0	4.20	1.01	277.30	260.29
11	32.0	4.52	1.06	275.52	263.84
12	33.0	4.86	1.11	273.68	267.45
13	34.0	5.21	1.16	271.73	266.18
14	35.0	5.56	1.20	269.70	262.14
15	36.0	5.94	1.26	267.50	260.85
16	38.0	6.72	1.37	263.00	258.20
17	39.5	7.34	1.45	259.21	256.18
18	40.5	7.77	1.51	256.41	243.33
19	41.0	8.00	1.55	254.98	214.66
20	42.0	8.44	1.61	251.82	210.39

Thus, the region where temperature is below dew point is shown as region of cloud formation.

Typical flow field features of cloud over the PSLV heat shield at transonic Mach number is given in Fig.7. The flow expansion is seen around the cone-cylinder junction and in this region the flow is supersonic. Due to this expansion, the local pressure reduces and in turn reduces the local temperature. Condensation phenomenon takes place when the relative humidity is 100%, i.e., when the local temperature equals the dew point. The shape of the cloud is determined by the isotherm lines and in Fig.7, the cloud is seen as having a conical shape and a flat base. Thus, the front cone shape is neither a shock wave nor a Mach wave; in fact, it is an isothermal line, whereas the flat base portion is a clear transonic shock wave. Generally, the condensation processes is terminated by a nearly flat transonic shock, across which the temperature increases above the dew point.

Results and Discussion

Figure 8 shows the temperature palette in grey scale for Mach numbers ranging from 0.77 to 1.61, where the maximum temperature limit is taken from the dew point distribution over the altitude at SHAR on 05.05.2005. As the Mach number increases from 0.77 (at 2.8 km), a very small pocket of condensation starts forming near the cone-cylinder junction of heatshield. This condensation cloud gradually grows in size and shape as the Mach number increases up to 0.94 (at 3.75 km) in the transonic regime. There is also a small cloud formation at the boat tail portion of the heat shield from Mach number 0.89 (at 3.46 km) onwards. At Mach number 0.96 (at 3.89 km) and 1.01 (4.20 km), the cloud seems to be reduced in intensity and size, this is due to the reduction in the local dew point. Again, the cloud shape is slightly increasing from Mach number 1.06 (at 4.52 km) to Mach number 1.11 (at 4.86 km). Between Mach numbers 1.11 (at 4.86 km) and 1.45 (at 7.34 km), the cloud is slanted backward and its size and shape remain nearly constant. The condensation cloud shape at the boat tail region is also slanted backward and it is clear. From Mach number 1.45 (at 7.34 km) onwards, the size of condensation cloud starts reducing and it is completely disappears at M=1.55 (at 8.00 km).

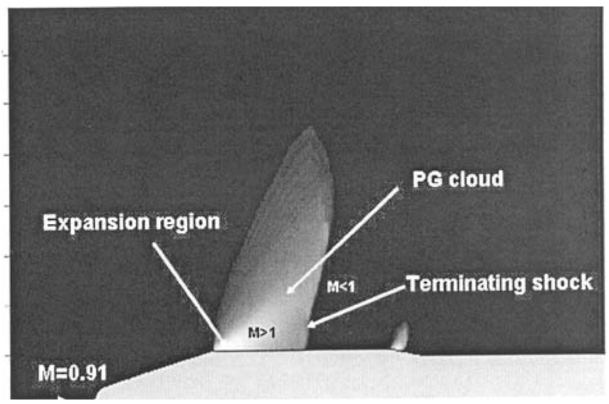

Fig.7 Details of condensation cloud structure

It is noticed that the transonic shock, which terminates the cloud formation at the rear is clear and nearly flat and straight upto Mach number 0.94 (3.75 km), above this Mach number, the transonic shock is slanted backward and weak.

At supersonic Mach numbers, the cloud is not seen; it is because (i) the dew point decreases at higher altitude compared to lower altitude and (ii) the upstream temperature ahead of cone-cylinder junction increases after passing through the detached shock in front of the nose cap, which prevents the local temperature from falling below the dew point.

Thus, the present investigation on cloud formation over the PSLV heatshield indicates the likelihood of cloud formation. This cloud formation is attributed to the *"Prandtl-Glauert Cloud"*, which occurs at transonic Mach numbers, where perturbations in the aerodynamics are large. At supersonic Mach numbers also the cloud formation takes place due to the dew point variation over altitude. The intermittent cloud formation over PSLV is probably due to the local fluctuation in the dew point. Exact simulation of cloud formation with heat release due to condensation of vapour and the effect of condensation cloud on aerodynamics require a two-phase flow analysis.

Conclusion

Cloud formation was seen around the heatshield region in the transonic and low supersonic Mach number regime of PSLV flight on 05.05.2005, from SHAR, India. This cloud formation is due to local condensation of moisture in the ambient air due to expansion of air in the transonic and low supersonic regime. CFD data is post processed in conjunction with dew point variation over SHAR on the day of launch. The results indicate the possibility of Prandtl-Glauert (PG) cloud formation around PSLV heatshield in the transonic regime and the condensation clouds are also observed in the low supersonic regime. The condensation clouds are formed over PSLV heatshield from Mach number 0.77 to 1.51. The intermittent cloud forma-

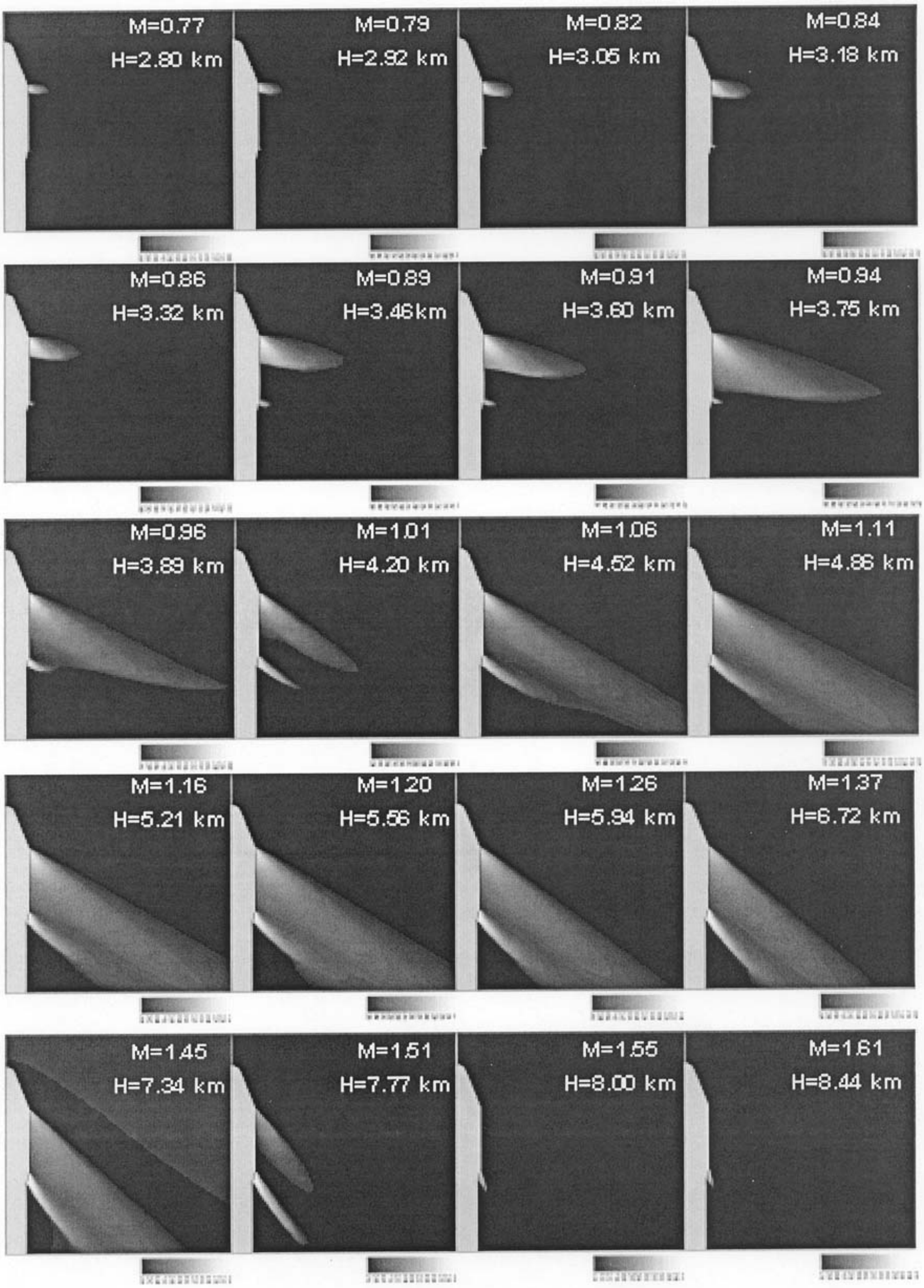

Fig.8 Local temperature below dew-point indicating condensation cloud formation

tion is probably due to the local fluctuation in the dew point. Similar cloud condensations are seen around aircrafts also. Exact simulations of condensation phenomenon require two-phase flow analyses.

Acknowledgments

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