NUMERICAL STUDY OF A PITOT PROBE WITH FIVE-HOLE PYRAMIDAL HEAD FOR SUPERSONIC FLIGHT TEST

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Abstract

During a flight of the airplane, the air data of the velocity vector such as Mach number, angle of attack and sideslip angle are important data to acquire the safe and consistence flight. JAXA (Japan Aerospace Exploration Agency) invented a Pitot probe with five-hole pyramidal head[1][2], which is able to more accurately measure velocity vectors. The accuracy and the beneficent of the five-hole Pitot probe has been validated by a flight test and wind tunnel tests. However the flow pattern and the effectiveness of the five-hole Pitot probe in detail were not clear, because the five-hole Pitot probe has complicated shape. In this study, we conducted CFD (Computational Fluid Dynamics) analysis to make clear the aerodynamic characteristic and the quality about the five-hole Pitot probe. The flow pattern and the aerodynamic characteristics in detail of the five-hole Pitot probe were made clear by the CFD analysis.

Nomenclature

α	angle of attack, degree
C_P	pressure coefficient
H	altitude, km
Re,u	Reynolds number based on 1 m length, 1/m
M	Mach number

1 Introduction

During a flight of the airplane, the air data of the velocity vector such as Mach number, angle of attack and sideslip angle are important to acquire the safe and consistence flight. Furthermore it is needed to obtain higher accurate air data for an experimental flight. In general, these data are measured with each separated measurement equipment. JAXA (Japan Aerospace Exploration Agency) invented the Pitot probe with five-hole pyramidal head[1][2] to measure accurate air data among the wide range of Mach number and angles of attack at the same time. Before a flight, wind tunnel tests had been performed to obtain the data table for the flight with the relationship between pressure coefficient, Mach number, angle of attack and sideslip angle. Then the data table was referred, and the velocity vector was identified during the flight.

The accuracy and the beneficent of the five-hole Pitot probe has been validated by flight tests and wind tunnel tests. However the flow pattern and the effectiveness about the five-hole Pitot probe in detail were not clear, because the five-hole Pitot probe has complicated shape. The purpose of this study is to make clear flow field around the five-hole Pitot probe using CFD (Computational Fluid Dynamics) analysis. The effects of Reynolds number, Mach number and the angle of attack were investigated by CFD analysis. The flow pattern and the aerodynamic characteristics in detail of the five-hole Pitot probe were made clear in this study. Furthermore, the improved idea for more accurate measurement of the five-hole Pitot probe was suggested by the CFD analysis.

2 Approaches

2.1 Pitot probe with five-hole pyramidal head

The Pitot probe with five-hole pyramidal head was developed by JAXA[1][2]. Figure 1 shows the five-hole Pitot probe configuration of the NEXST-1 (National Experimental Supersonic Transport) airplane[3] located on a starboard side of the NEXST-1 airplane's nose. The five-hole Pitot probe is composed a square truncated pyramidal shape with five holes. Figure 2(a) is a front view and Fig. 2(b) is a partial side sectional view. A total pressure hole is located in the center(P_H). Four groups of pressure taps (P1-P4) are located on each slanted surface of the pyramidal shape. The five pressure taps of each group are integrated with a pressure tubing. The five-hole Pitot probe is composed with four pressure tubes of the slanted surface and a total pressure tubing as a whole. Therefore "five-hole" means that the five-hole Pitot probe has five measurement tubes. In this study, the five holes on the slanted surface are described "pressure taps" to distinguish the "five-hole Pitot probe". These pressure tap groups can derived its flight velocity vector. The multi taps on the each slanted surface are effective to avoid an accident with being choked by any dusts. And there is another tube around the total pressure hole to prevent flow separation in front of the total pressure hole, called the "Kiel tube". The Kiel tube is connected to atmosphere by vent hole (See Fig. 2). Because the pressure at the vent hole is lower than the pressure in front of total pressure hole, the flow in the Kiel tube is prevented to flow separation near the front of the total pressure hole and the leading edge of the slanted surface.

The five-hole Pitot probe was mainly used for experimental airplanes in JAXA, because the five-hole Pitot probe can be measured the air data with high accuracy: for example, ALFLEX (Automatic Landing Flight Experiment)[4], HOPE-X (H-II Orbiting Plane Experimental)[5] and NEXST-1[3]. All those experimental flight was conducted successfully with the five-hole Pitot probe. In this paper, we will introduce about the NEXST-1 project, which airplane is one of the most important instance. As Fig. 3 shows, the experimental airplane was launched using a rocket booster, and accelerated to M=2.3 at an altitude of 19 km. The airplane was separated from the rocket, and started to glide through its aerodynamic measurement phases. The mach number of the measurement phase is around 2. After the measurement phases, the airplane reduced its flight speed and descended, and finally touched down using a parachute and air bags. The aerodynamic data were measured[6], and the experimental airplane was recovered safely. During the flight test, the airplane was automatically controlled from M=2.3 to M=0.3 by the air data measured with the five-hole Pitot probe.

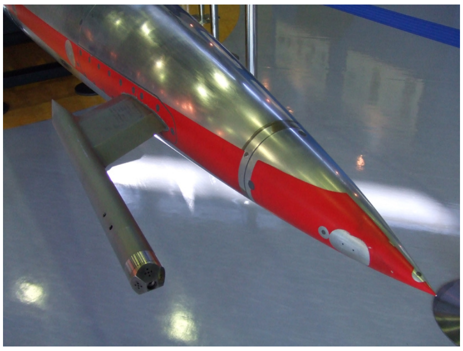
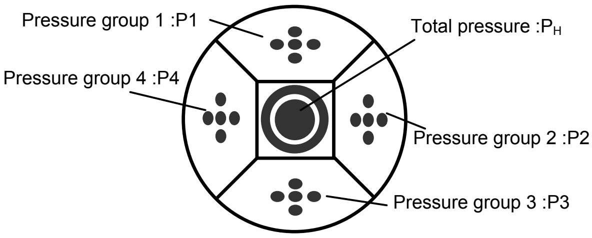
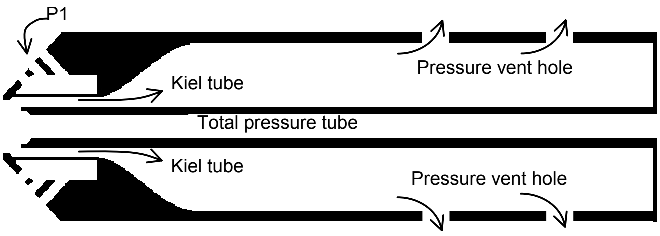


Fig 1. The Pitot Probe of NEXST-1



(a) Front View



(b) Side View

Fig 2. The Pitot Probe with Five-Hole Pyramidal Head

Fig 3. The NEXST-1 Airplane

2.2 CFD analysis method

In this study, CFD analysis conducted by means of UPACS (Unified Platform for Aerospace Computation Simulation)[7] code. The UPACS is the structured mesh code developed by JAXA, and is a standard CFD code in the Institute of Aerospace Technology of JAXA. The governing equation is the Navier-Stokes equation and Splart-Allmaras one equation model is used to simulate turbulent flow. The Navier-Stokes flow solver of UPACS is based on a cell-centered finite volume method. The convection terms are discretized using Roe's flux difference splitting with the MUSCL. The MFGS (Matrix Free Gauss-Seidel) implicit method is used for time integration.

Figure 4 shows the shapes of the five-hole Pitot-probe for CFD analysis. There are three types configurations for more accurate CFD analysis. "CFD1" shape is a only truncated pyramid shape without the total pressure tubing and the Kiel tube. "CFD2" has a simple and cylindrical total pressure sensor, and simple Kiel tube. The boundary condition of the end of Kiel tube is exit flow condition using extrapolation. "CFD3" is modified the Kiel tube, and added the pressure vent hole and the total pressure tubing. The cylindrical part of total pressure tubing was changed into the actual tube shape. "CFD3" is similar to the actual five-hole Pitot probe. All of them have non pressure taps, because it is difficult to solve the detail five-hole Pitot probe with the pressure taps on the slanted surface even by CFD analysis.

Because there is a large cavity in the five-hole Pitot prove of the CFD3 as the actual five-hole Pitot probe, it is difficult to solve under high speed condition (M=2). The CFD3 was started computing from M=0.2, then Mach number was increased step by step for M=2.

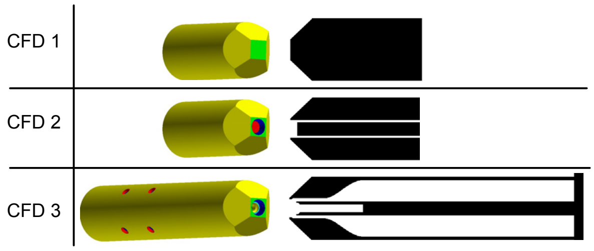


Fig 4. The Pitot Probe Shape for CFD Analysis

2.3 Wind tunnel tests

Wind tunnel tests were performed at 1m×1m JAXA supersonic wind tunnel. Figure 5 shows a wind tunnel model of the five-hole Pitot probe. The five-hole Pitot probe was located at the center of the wind tunnel to avoid the interference by the wall. The model scale and geometry was as same as the Pitot probe installed to the NEXST-1. The range of Mach number was between 1.4 and 2.2, and the angle of attack was swept from 0 to 4 degree by pitch and pause method. The Reynolds number is $27x10^6$ (1/m).

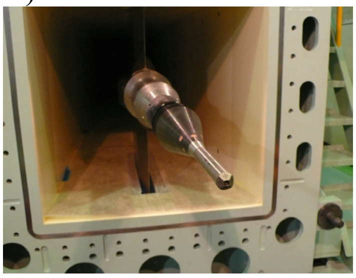


Fig 5. Wind Tunnel Test

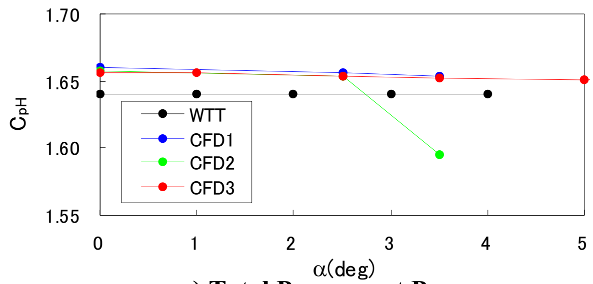
3 Results and Discussions

3.1 Validation of the CFD analysis

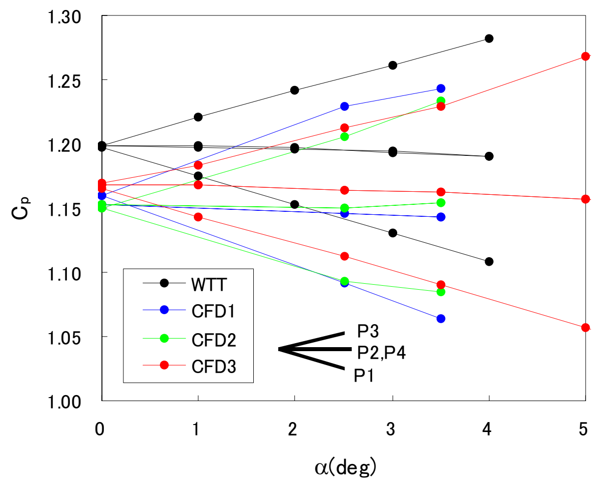
Figure 6 shows the pressure coefficient value (C_P) obtained from the CFD analysis and the wind tunnel tests. At first, see the wind tunnel test results (black line). It is recognized that the total pressure C_{PH} values are almost constant and the C_{P1}- C_{P4} are linear on the all angles of attack.

The total pressures (C_{PH}) of CFD are evaluated on the axial center point. The C_{P1}- C_{P4} values of the pressure groups at slanted surface are average values at same points corresponded to the locations of the five pressure taps for each group. It is found that the C_{P1}- C_{P4} of the CFD1 and CFD2 is lower than the CFD3 and the wind tunnel test results. Furthermore, the CFD3 and the wind tunnel test results are more linear than the CFD1 and the CFD2. The results suggest that the CFD3 and the wind tunnel test were qualitatively corresponding, because the geometry of the CFD3 is more similar to the wind tunnel test model than the CFD1 and CFD2. However there were quantitative differences about the pressure taps on the slanted surface between the CFD3 and the wind tunnel test. It is a cause that there is non pressure tap on the slanted shape of the CFD analysis due to the complexity of the pressure taps on the slanted surface. If we needed to obtained the data table of the five-hole Pitot probe without wind tunnel test results, it would be performed CFD analysis with the pressure taps. However it was assumed that the CFD analysis with the Kiel tube except the pressure taps on the slanted surface can be understood the aerodynamic characteristic of the five-hole Pitot probe.

Figure 7 to 9 show surface C_P distributions and the surface flow pattern on the CFD1 to the CFD3. As in Fig. 7, the CFD1 has the widest separated regions in the CFD analysis, because of non-effect by the Kiel tube. As in Fig. 9, the separation region on the CFD3 is narrower than the other CFD analysis. So it is suggested that the Kiel flow is important for estimation of the C_P on the slanted surface. In this study, it was assumed that the CFD3 is the nearest to the wind tunnel test and the actual five-hole Pitot probe. Thus a "CFD" in below sections shows the CFD3 analysis. Figure 10 shows the Mach number distribution of the CFD3 at α=0 degree on the cross section included the axial center and the upper pressure vent hole. The flow velocity is slow down through the bow shock, then it is accelerated in the Kiel tube by low pressure at the vent holes. It is found that there is no separation region in front of the total pressure hole even at 3.5 degree condition. Therefore, the effect of the five-hole Pitot probe can be cleared by the numerical analysis.

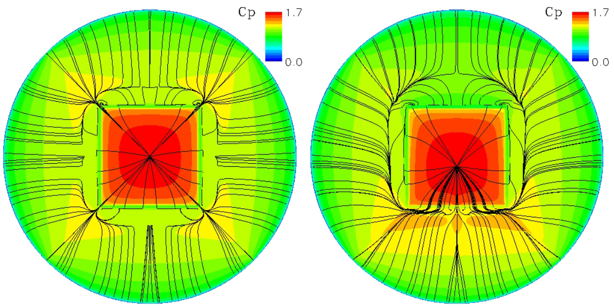


a) Total Pressure at P_H



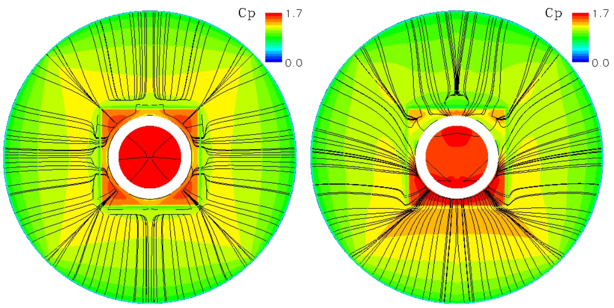
b) Static Pressure at P_{1-4}

Fig 6. Comparison the Wind Tunnel Test and CFD



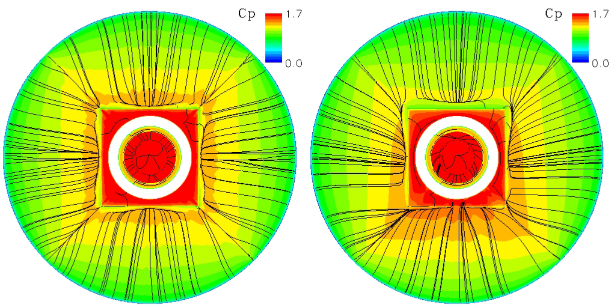
a) α=0deg b) α=3.5deg

Fig 7. C_p Distribution of CFD1



a) α=0deg b) α=3.5deg

Fig 8. C_p Distribution of CFD2



a) α=0deg b) α=3.5deg

Fig 9. C_p Distribution of CFD3

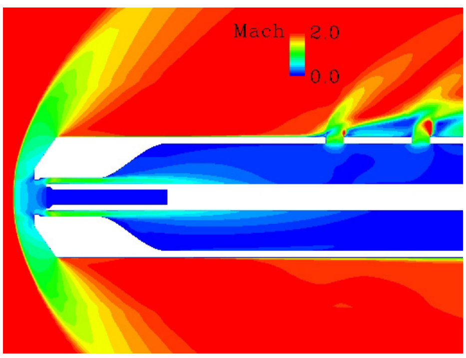
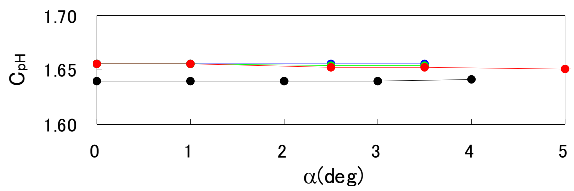


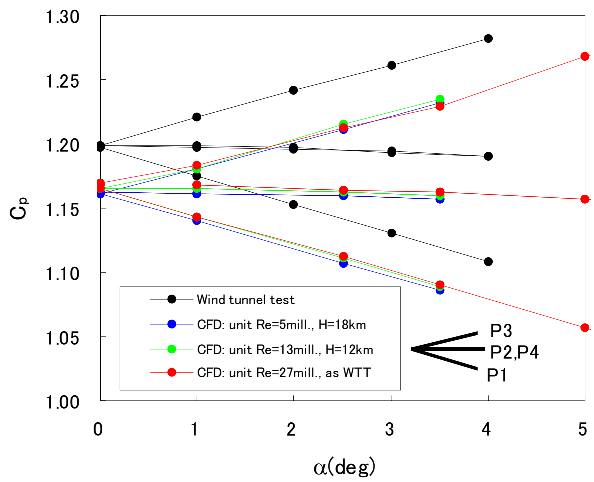
Fig 10. Mach Distribution of CFD3 at α=0deg on the cross section including the center and pressure vent hole

3.2 The effect of Reynolds number

This five-hole Pitot probe was designed as available at wide Reynolds number conditions. The effect of Reynolds number was confirmed by CFD analysis. Figure 11 shows the C_P value of the CFD analysis in different Reynolds number condition and the wind tunnel test results. The CFD analysis were done in different Reynolds number condition from the wind tunnel test to the flight test conditions. It is found that a significant difference is not observed by the three CFD results, though there are differences in the wind tunnel test results and the CFD results. It has been confirmed that the differences do not influence to the data table for the flight. Thus it was recognized that there is no influence of the Reynolds number effect. It was suggested that the results on low Reynolds number condition can be applied to the high Reynolds number conditions.



a) Total Pressure at P_H

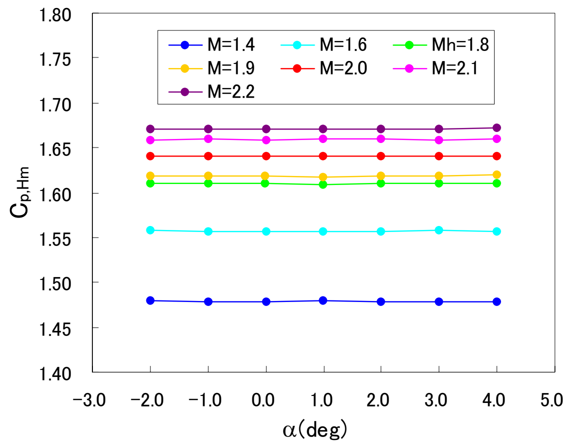


b) Static Pressure at $P_{1\text{-}4}$

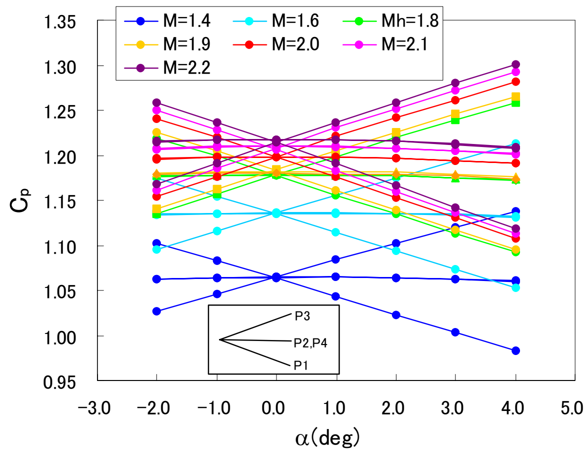
Fig 11. Comparison of the Wind Tunnel Test and CFD on the different Reynolds number.

3.3 The effect of Mach number

The relation between the Mach number and C_P was clarified by changing the Mach number from 0.2 to 2.2 by the wind tunnel test and CFD analysis. Figure 12 shows C_P values of the wind tunnel test results when the Mach number is changed from 1.4 to 2.2. It is found that the C_{PH},C_{P1}-$_{P4}$ rose as the Mach number increased. CFD analysis were also conducted by changing the Mach number form 0.2 to 2.0. Figure 13 shows the Mach number effect of the wind tunnel test and the CFD at α=0 degree. The $C_{P,average}$ means a average value between C_{P1} to C_{P4}. However both of the wind tunnel test's C_P and the CFD's C_P rose as the Mach number increased, the increasing rates are non-linear. The similar tendency was observed, though there is quantitative difference. Thus it was determined by the above data that it should be taken the every M=1.0 data, and approximated with second or more order interpolation.



a) Total Pressure at P_H



b) Static Pressure at P_{1-4}

Fig 12. Mach Number Effect of Wind Tunnel Test

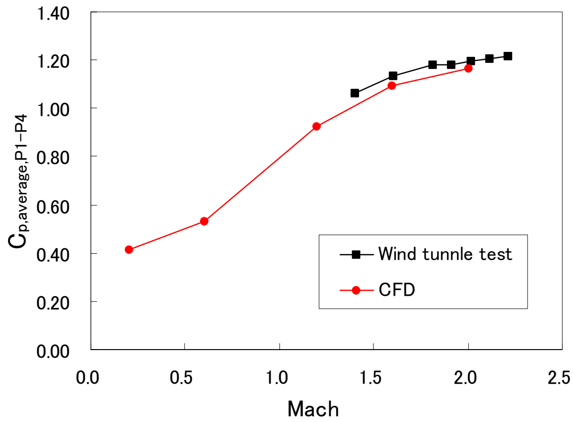
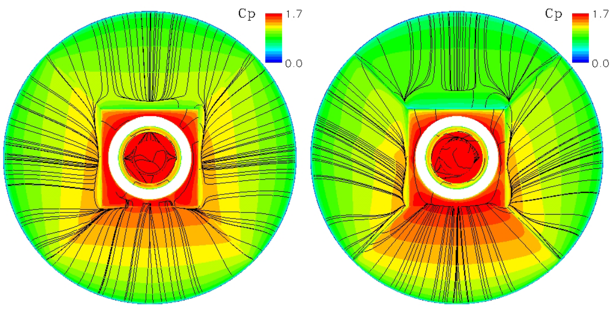


Fig 13. Mach Number Effect of Wind Tunnel Test and CFD at α=0 degree

3.4 The effect of the angle of attack

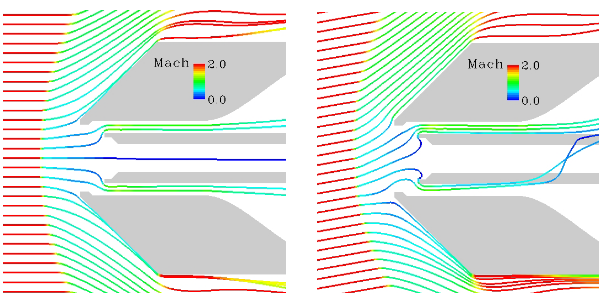
Finally it was investigated that the effect of the angle of attack with the CFD analysis. Figure 14 shows the C_P distributions and the surface flow on the head of the five-hole Pitot probe at α=5 degree and α=10 degree by the CFD analysis. Despite the high angle of attack as in Fig 14(b), the separation region was prevented the influence to the pressure taps. This reason is explained from the effect of the Kiel tube and the pressure vent holes as in Fig.15. Figure 15 shows the stream line and the magnitude of the velocity in the symmetry plane of the five-hole Pitot probe head. Figure 15(a) and (b) show at α=0 degree and α=10 degree. Both of the angles of attack as in Fig.15(a) and (b), the flow velocity is slow down under sound speed through the bow shock at first. The subsonic stream line out of the five-hole Pitot probe flow along the slanted surface, then they are accelerated to approximately M=2 on the corner of the end of slanted surface. On the other hand the stream lines in front of the total pressure hole was sucked into the Kiel tube and accelerated over supersonic in the Kiel tube because of the low pressure at the vent hole. Thus the separation in front of the total pressure hole is prevented by the effect of the suction by the Kiel tube even at a=10 degree. When the angle of attack is 10 degree as in Fig.15(b), the growth of separation is prevented by the effect of the Kiel tube and the pressure vent hole, though there is small separation in front of the total pressure hole. The fact is indicated that the five-hole Pitot probe is effective on the high angle of attack.

Having clarified the effect of the five-hole Pitot probe at the high angle of attack, the location of the pressure taps for each pressure group on the slanted surface will be discussed. While it is found that there are the C_P gradients along the down stream direction from Fig. 14, there are not gradients of the C_P on the perpendicular direction. In other words, the C_P values are not obvious changed along the perpendicular direction in spite of the high angle of attack. The five or multi pressure taps on the each slanted surface are located to avoid being choked by some dusts. According to the CFD analysis, it was recognized that an arrangement of the location of the pressure taps can improve the accuracy to change the allocation of the pressure taps on each slanted surface into a linear form along the perpendicular direction to the down stream.



a) α=5deg b) α=10deg

Fig 14. C_p Distribution and Surface flow of CFD (α=5deg, α=10deg)



a) α=0deg b) α=10deg

Fig 15. Mach Number and Stream line Around Pressure hole of CFD (α=0deg, α=10deg)

4 Conclusion

Wind tunnel tests and CFD analysis about the Pitot probe with five-hole pyramidal head were performed to make clear its flow pattern and to improve its performance.

(1) The CFD analysis by detailed geometry of the five-hole Pitot probe and the wind tunnel tests were qualitatively corresponding, though there were quantitative differences due to approximation on the CFD analysis.

(2) It was confirmed that there is no influence of the Reynolds number. Therefore the data base from the wind tunnel test can be applied to the actual flight.

(3) It was determined by the investigation of the effect of mach number that it should be taken the every M=1.0 data, and approximated with second or more order interpolation.

(4) The Kiel tube is effective to prevent flow separation in front of the total pressure hole at wide a ranges by the Kiel tube.

(5) It was suggested that an arrangement can improve the better by change the pressure taps allocation on the slanted surface.

We will apply to an actual flight of a airplane using the information of this study. And further research on CFD analysis by more detail shape would clarify the effect of the Pitot probe with five-hole pyramidal head.

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