Air Condensation in a Hypersonic Wind Tunnel

FRED L. DAUM*

Aeronautical Research Laboratories, Wright-Patterson Air Force Base, Ohio

Air condensation studies were conducted in a 3-in. hypersonic wind tunnel where the flow Mach numbers ranged from 9.5 to 17.0. The stream pitot and static pressures both were found to be affected strongly by the presence of condensation. Large amounts of apparent supersaturation, which increased with increasing Mach number, were found to exist. It was shown that hypersonic wind tunnels may be operated with stagnation temperatures much lower than those temperatures required for avoiding saturation conditions in the air stream, and single-phase flow still may be maintained.

FOR the past two decades the problems arising from the occurrence of air condensation in hypersonic nozzles have been of great concern to the operators and designers of hypersonic wind tunnels. When condensation occurs, isentropicity is lost, and meaningful data no longer are obtained. This phenomenon of air condensation may occur when the decreasing pressure and temperature of the expanding flow reach or exceed the air saturation point conditions. At this point the air may begin to condense or it may continue to expand into a supersaturated state. To avoid condensation, the air may be heated to stagnation temperatures sufficiently high that the static air temperatures throughout the expansion are greater than the saturation temperature. However, at high Mach numbers this approach becomes impractical because of the prohibitively high stagnation temperatures required.

A number of early studies[1–9] of air condensation in wind tunnels were made in the period of 1948 to 1953 in the Mach number range of about 5 to 7. Most of these studies showed that condensation occurred at, or very soon after, the point where the stream reached saturation conditions. More recently, in 1960, Dayman[10] at the Jet Propulsion Laboratory reported that appreciable levels of supersaturation could be achieved at Mach numbers up to 9.5. Subsequently, Lee and Gregorek at Ohio State University showed with unpublished data that, at Mach numbers greater than 10, large, significant amounts of supersaturation apparently could be obtained. The present study was undertaken for the purpose of extending and gaining more complete knowledge of the phenomenon of air condensation. In particular, the objectives were to determine the influence of air condensation on the pressure characteristics of the flow and to establish the operational limits of the facility for maintaining condensation-free flow in terms of Mach number and stagnation pressure and temperature.

Experimental Test Facility

The present experimental study was carried out in a blowdown type of wind tunnel which exhausts dried air from a storage system having a maximum pressure of 3000 psi through the tunnel and into a 35,000-ft^3 vacuum sphere having a minimum vacuum pressure of about 5 mm Hg absolute. The air is dried to an average dewpoint temperature of -65°F, corresponding to 25 parts of water per 10^6 parts of air by volume. A resistance-type, 25-kw electric heater capable of delivering air at about 2200°R stagnation temperature is used. The tunnel uses a free-jet type of test section and is equipped with four interchangeable conical nozzles having geometrical area ratios corresponding to Mach numbers 10, 12, 15, and 17. These nozzles deliver nominal Mach numbers of 9.4, 10.5, 13, and 16, respectively, on the centerline at the nozzle exit. For convenience, the nozzles hereafter are identified by the geometrical Mach number. The nozzles each were equipped with several wall static orifices in the downstream end which were spaced at 1-in. intervals. The orifice diameter used was 0.047 in. The axial and lateral Mach number gradients ranged from 0.4 to 0.8 Mach number M/in. and from 0.2 to 0.8 M/in., respectively, for the M 10 through the M 17 nozzles. The Reynolds numbers covered in the study ranged from 0.175×10^6 to 0.600×10^6/ft.

Instrumentation

Total pressure measurements were made with Wallace and Tiernan gages of either 50 or 100 mm Hg full scale range; static pressures were measured with Ace McLeod gages. The stagnation temperature was sensed by a platinum-rhodium-platinum thermocouple and recorded on a Brown potentiometer. Stagnation temperature readily was controlled to within ± 5°R. The stagnation pressure was indicated and recorded by a Brown potentiometer and was controlled manually to within about $\pm 1\%$ of the indicated value.

The pitot pressure probes were $\frac{1}{8}$ in. in diameter with flat ends having an opening 0.078 in. in diameter. All probes and orifices were short-coupled to minimize pressure stabilization times.

Test Procedure

The primary measurements made consisted of pitot and static pressures measured at fixed locations near the nozzle exit as the stagnation temperature was varied. It was found that, unless a considerable dwelling time was allowed at each temperature, undesirable hysteresis effects appeared. To minimize these effects, the procedure used was first to increase the stagnation temperature to a stable maximum desired temperature and then to stabilize at discreet values of successively lower temperatures. In reducing data obtained at stagnation temperatures greater than 1000°R, the customary corrections for caloric imperfections were made using the procedures of Ref. 11.

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* Aeronautical Research Engineer, Hypersonic Research Laboratory. Member AIAA.

Methods for Determining the Onset of Condensation

Two methods for determining the onset of condensation were selected from a number of techniques tried. These methods made use of accurate measurements of the static pressure p and the pitot pressure, P_0' obtained over a range of stagnation temperatures T_0. To obtain these measurements, the stagnation temperature T_0 was lowered in increments from the maximum experimental value while the stagnation pressure P_0 was held constant. The measured pressures remained essentially constant, except for a weak Reynolds number effect, until a critical T_0 value was reached, whereupon the pressures began to show marked changes. The initial point of sharp pressure deviation, $(T_0)_c$, was interpreted as the start of condensation. It is noteworthy that for the Mach 10 and Mach 12 nozzles it was possible to attain stagnation temperatures that were appreciably greater than the theoretical stagnation temperature required for avoiding condensation, $TH\ (T_0)_c$, at the nozzle exit. Therefore, the assumption that the onset of condensation coincides with the initial strong pressure change that occurs as T_0 is lowered appears justified, inasmuch as no other extraneous effects, except the mild Reynolds number influence, are expected. For the Mach 15 and Mach 17 nozzles, the maximum T_0 values obtainable were considerably below $TH\ (T_0)_c$. However, the strong pressure variations, which were observed as T_0 was lowered, had the same characteristics as the pressure changes in the Mach 10 and Mach 12 nozzles; this is evident in Fig. 1. Therefore, it appears reasonable to assume that the break in the p and P_0' pressure curves for the higher Mach number nozzles also is due to condensation effects and thus also indicates the onset of condensation.

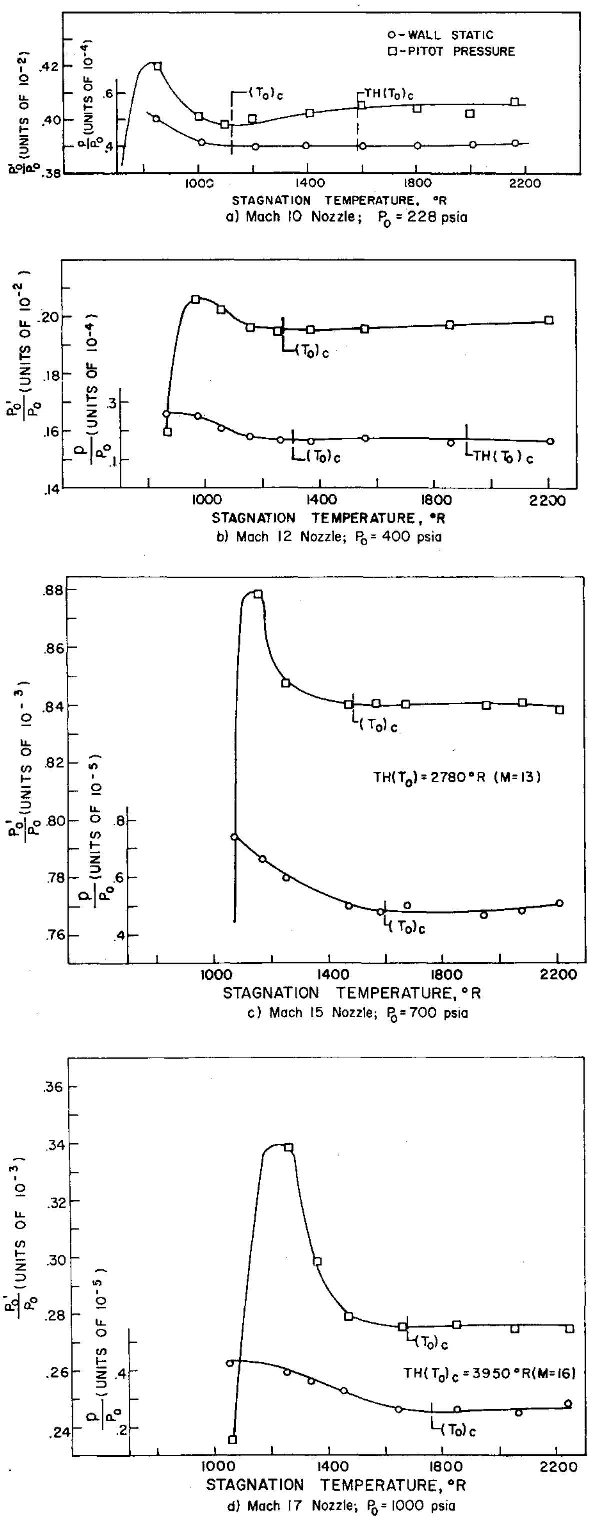

Fig. 1 Pitot and static pressure measurements indicating onset of condensation

Results and Discussion

Typical variations of the pitot and static pressures indicating the onset of condensation are presented in Fig. 1. It is readily evident that the pressure breakaway point $(T_0)_c$ occurs at increasingly higher stagnation temperatures as the Mach number increases. It may be noted in Fig. 1 that some minor Reynolds number effects are present which are characterized by the slightly sloping curves at temperatures above the breaking point; however, it is seen that the pressure changes due to condensation strongly override the Reynolds number effects. The pitot and static pressures are shown to be about equally sensitive to condensation, which was not the case found by the early investigators working generally at lower Mach numbers, where it was shown that the pitot pressure was completely unaffected by condensation. The behavior of the pitot pressures in the presence of condensation, as shown in Fig. 1, is not readily explainable; it appears that complex phenomena occur which involve the strong gradients across the bow shock wave on the pitot probe, relaxation times, and re-evaporation rates.

It should be noted that, although the nozzles were geometrically conical in shape, conical flow was not achieved. This was because of the rapid nonlinear growth of the boundary layer through the nozzle which resulted in a general compression from the centerline toward the wall. Thus, the Mach number was higher on the centerline than at the boundary layer. This effect was slight in the Mach 10 nozzle but increased with Mach number. Therefore, in Fig. 1, the $(T_0)_c$ value indicated for the pitot probe is different from that shown for the wall static pressure measurement.

The equilibrium-saturated expansion theory of Buhler and Nagamatsu[9] was shown in their work at the Guggenheim Aeronautical Laboratory of California Institute of Technology to be quite useful in describing various features of the condensation phenomenon. This theory (details of which are described elsewhere) was applied to the present case. The primary postulation of the theory is that the expansion through the nozzle follows the isentrope in the pressure-temperature plane until the air saturation curve, which has a steeper slope than the isentrope, is intersected. Further expansion then follows along the air saturation curve.

In the equilibrium-saturated expansion theory and elsewhere in this study, reference is made to the air saturation curve. Because of the lack of air vapor pressure data in the low pressure and temperature ranges of interest, a simplified air saturation curve was established. Wagner's air saturation curve, as used by Buhler[9] and others, was extrapolated in the linear plot of $\ln p$ vs $1/T$. However, because of various uncertainties regarding the accuracy of this extrapolation, any determination of a supersaturation, which necessarily refers to the saturation curve, will be termed an "apparent supersaturation." The absolute accuracy of this curve does not bear a strong influence on the primary conclusions that are reached.

Applying the equilibrium-saturated expansion theory, the static pressures, in the presence of condensation, were computed. A typical case is presented in Fig. 2, where the ratio of the pressure with condensation to the pressure without condensation is plotted vs stagnation temperature. The pressure without condensation was taken as the value at the breakaway point $(T_0)_c$ (Fig. 1). It is seen that the general rise of static pressure, after the onset of condensation, is predicted well by the theory.

The static pressure distributions through the nozzles were computed using the same theory. In Fig. 3 are shown typical theoretical pressure distributions for one nozzle (Mach 17) evaluated at various stagnation temperatures and constant stagnation pressure. Without condensation, the complete expansion would be along the isentrope shown. The theory indicates that when the air saturation conditions are reached the expansion begins to deviate from the isentropic case. It appears that there is a weak tendency for the experimental pressure distribution, with condensation, to approach the theoretical values; this is similar to the results of Grey and Nagamatsu[6] at lower Mach numbers.

The static pressures related to the observed onset of condensation points for the four nozzles used are plotted against the corresponding static temperature in Fig. 4 along with the saturation curve for air. Data from the present study are shown as the solid symbols. A distinction is made between the points established from static pressure measurements and from impact measurements. This is to illustrate that the impact pressures appear to indicate a slightly greater supersaturation than do the wall static pressures. Also shown in Fig. 4 are some data points obtained at lower Mach numbers by other investigators. It is interesting that these data points group along the line labeled "onset of condensation," although the nozzle size and the stagnation conditions of the various facilities vary appreciably.

Two items of particular interest in Fig. 4 are 1) the point of intersection A of the experimental onset of condensation curve with the saturation curve (actually determined by the Jet Propulsion Laboratory data), which implies that no supersaturation should be obtained at stream pressures greater than about 3.5 mm Hg; and 2) the trend of the experimental onset of condensation curve to parallel the saturation curve at the low pressure end, which implies that a maximum asymptotic value of apparent supersaturation is being approached.

At the end of the present study a brief attempt was made to verify experimentally the point of intersection of the onset of condensation with the saturation curve shown in Fig. 4. To obtain the proper pressure and temperature conditions, it was necessary to make measurements in the nozzle at points far upstream from the nozzle exit and approaching the nozzle throat. The measurements indicated that an apparent supersaturation was obtained far upstream in the nozzle, but a shift away from the original onset of condensation curve was obtained also; this approximate shift for the Mach 10 and 12 nozzles is indicated by the dashed lines in Fig. 4. In trying to explain this discrepancy, the work of the earlier investigators was again reviewed and it was noted that all of the Jet Propulsion Laboratory, Aeronautical Laboratory of Ohio State University, and Naval Ordnance Laboratory data shown in Fig. 4 were obtained at either the nozzle exit or the test section, and the nozzles generally were larger than the 3-in. hypersonic wind tunnel nozzles. The significant point is that the measurements were made a considerable distance downstream of the nozzle throat. However, in the GALCIT tests[6–8] a 5-in. nozzle was used and the measured pressure

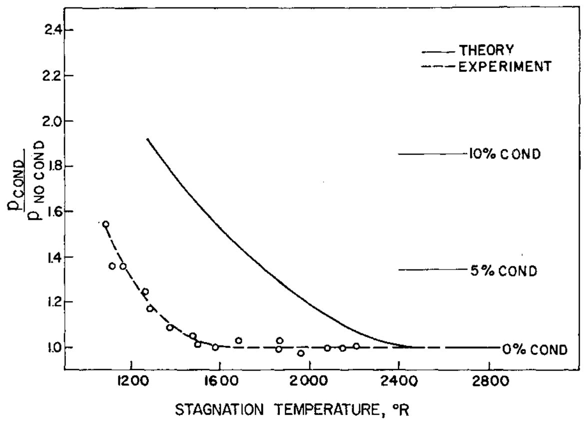

Fig. 2 Typical effect of air condensation on wall static pressure at nozzle exit, Mach 17 nozzle, P_0 = 1000 psia

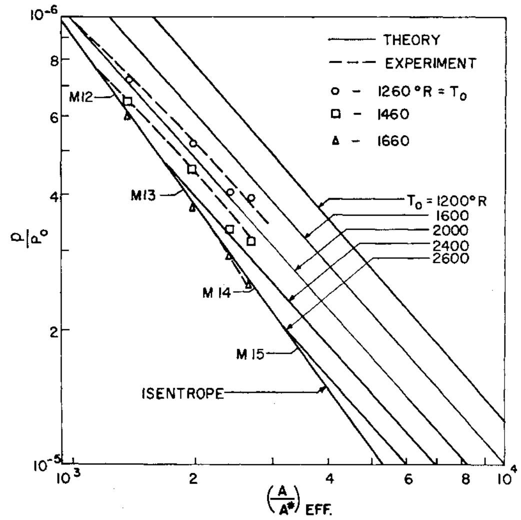

Fig. 3 Typical influence of air condensation on nozzle wall pressure distribution; M 17 nozzle, P_0 = 1000 psia

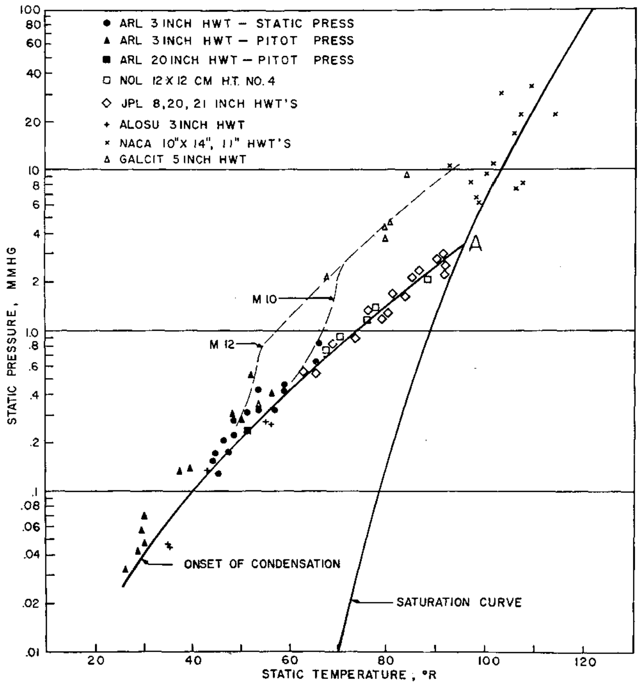

Fig. 4 Stream pressure and temperature conditions at the onset of air condensation

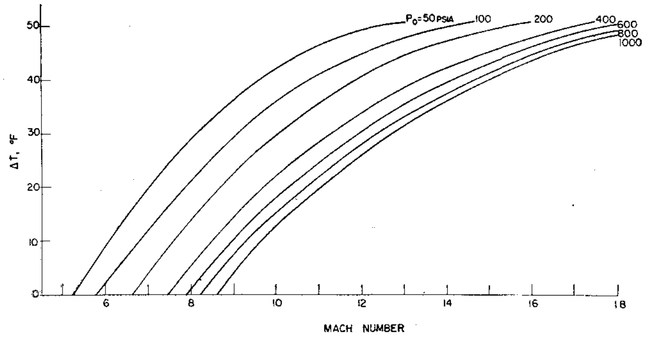

Fig. 5 Apparent supersaturation at onset of condensation

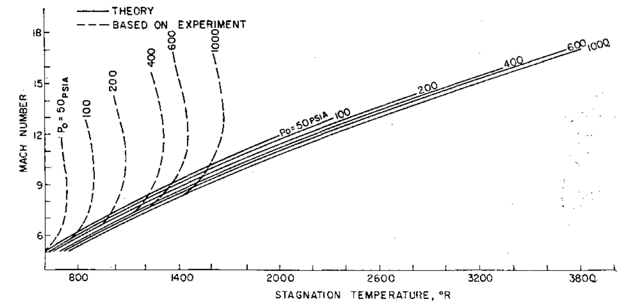

Fig. 6 Limiting stagnation temperature corresponding to onset of condensation

distributions extended far upstream in the nozzle. The GALCIT tests indicated that some supersaturation was obtained, but it also was in the region of the dashed line in Fig. 4. However, for one set of GALCIT 5-in. tunnel data presented by Nagamatsu,[8] the onset of condensation point determined near the nozzle exit agrees with the presently established onset curve; this point is shown at a pressure of about 0.34 mm Hg. The NACA experimental studies[3-4] were made in a relatively large 10- by 14-in. tunnel and an 11-in. tunnel but at stagnation pressures sufficiently high that supersaturation would not be expected, based on the present results.

Thus, it appears that if the onset of condensation is determined sufficiently far downstream of the nozzle throat it will correspond to a point on the condensation onset curve presented in Fig. 4. If the nozzle is small or if the condensation measurements are made far upstream in the moderately sized nozzle, it appears that the start of condensation will be along the dashed line of Fig. 4. As an explanation of this phenomenon, it is suggested that a time lag may become involved when air condensation occurs in the presence of steep pressure, temperature, and velocity gradients.

The amount of apparent supersaturation ΔT to be expected as a function of Mach number is presented in Fig. 5, where stagnation pressure is a parameter. It is seen that at low Mach numbers the expected apparent supersaturation ΔT is low but increases rapidly with increasing Mach number. The effect of stagnation pressure on ΔT is strong at the low hypersonic Mach numbers but becomes weak at high Mach numbers. It appears that ΔT is approaching an asymptotic maximum value of about 55°F.

The stagnation temperatures representing the onset of condensation, based on the experimental study results, are shown as the broken lines in Fig. 6 as a function of Mach number, with P_0 as a parameter. Also shown, as the unbroken curves, are the theoretical values of T_0 for which the air becomes saturated. The horizontal spread between the broken and the unbroken curves is indicative of the degree of apparent supersaturation in terms of stagnation temperature. The tremendous gain in stagnation temperature which is possible by operating high Mach number nozzles with the air in an apparent supersaturated state clearly is evident.

Summary and Conclusions

An investigation of the air condensation phenomenon occurring at the exit of rapidly expanding hypersonic nozzles has shown that large amounts of apparent supersaturation may be obtained. Therefore, single-phase isentropic flow may be achieved at stagnation temperatures considerably below the theoretically required temperatures for obtaining condensation-free flow with no supersaturation.

It was found that the pitot pressure is equally sensitive to condensation effects as the static pressure, but that the pitot pressure will indicate a slightly lower stagnation temperature requirement for avoiding condensation than does the static pressure. The equilibrium-saturated expansion theory was shown to be adequate for predicting the general rise in static pressure due to the latent heat of condensation.

It appears that there is a limiting stream static pressure range (about 4 mm Hg) above which air supersaturation will not occur. However, there is evidence that the limiting pressure and temperature conditions, which define the onset of condensation at the nozzle exit, do not apply to the upstream portion of the nozzle where low hypersonic speeds exist. It is believed that an apparent supersaturation that occurred far upstream of the nozzle exit likely was due to the presence of severe pressure, temperature, and velocity gradients, resulting in a time lag in the condensation process.

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