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AN EXPERIMENTAL STUDY OF TRANSONIC FLOW PAST A SPHERE

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ABSTRACT

Detailed measurements of the pressure distribution around a sphere were made in the ranges of $0.4 \leq M_\infty \leq 1.0$ and $1.7 \times 10^5 < Re < 1.2 \times 10^6$. Distinctions have been made of the distributions before and after the critical Reynolds number. The effects of the free stream Mach number in the region of the critical Mach number have also been investigated. The presence of the shock near the surface of the sphere has profound interactions with the boundary layer and consequently plays an important role in the resulting pressure profile. The experiment has provided new data for transonic flow around a sphere in the ranges of critical Mach and Reynolds numbers.

INTRODUCTION

The problem of transonic flow around axisymmetric bodies has long been considered as fundamentally important in the area of compressible fluid dynamics. This is because of its wide applications in missile and aircraft aerodynamics, and also as velocity probes in subsonic and supersonic flow fields. Despite the perfect symmetry of the sphere, which has been an ideal target for a number of experimental, analytical and numerical fluid dynamics, there has been a significant lack of data, as reviewed by Miller and Bailey (1979), in the critical ranges of Mach (M_∞) and Reynolds (Re) numbers.

The critical Mach number, M_{crit}, which is the free stream Mach number at which the maximum velocity of the potential flow fluid past the sphere is just equal to the local velocity of sound, was evaluated by Kaplan (1940) to be 0.573. In low subsonic flow, the critical Reynolds number, Re_{crit}, generally falls in the range of $3 \times 10^5 < Re < 1 \times 10^6$, as summarised by Maxworthy (1969). However, Naumann (1953) has made extensive drag measurements in the ranges $10^5 < Re < 6 \times 10^5$ and $0.3 < M_{crit} < 0.9$ and found that Re_{crit} increases with M_∞ when $M_\infty > 0.35$.

There have been very few measurements of pressure distribution on the surface of a sphere in this region of M_{crit} and Re_{crit}. Jaikrishnan et al (1977) had made some experimental and numerical studies on transonic flow past a sphere. The range of Re considered by them was limited and the pressure measurements were confined to an angle of up to 60° from the front nose of the sphere. With the recent advance in Computational Fluid Dynamics, there is an increasing demand for experimental data in these interesting ranges of flow conditions for the verification of the numerical techniques. It was, therefore, the intention of the authors that the present experiment would provide extensive pressure distribution data in the free stream Mach number range of $0.40 \leq M_\infty \leq 1.00$ and at $2 \times 10^5 < Re < 1.5 \times 10^6$, thus filling in the void of the data available in this fundamental area of fluid mechanics.

THE EXPERIMENT

The experiment was carried out in the Variable Pressure Transonic Wind Tunnel at the Aeronautical Research Laboratory of Defence Science and Technology Organization (DSTO), Melbourne. The cross-section of the test section was rectangular and was 533 mm wide by 813 mm high. The side walls were solid. The top and bottom walls were slotted longitudinally and had an open area ratio of 16.5%.

The sphere, of diameter 130 mm, was made of admiralty bronze and had a smooth polished surface. There were 35 holes of diameter 0.8 mm drilled perpendicularly to the surface of the sphere for pressure measurements. They were arranged in such a way that static pressures on the surface of the sphere may be measured at an angular position of θ from 0° to 165°, where $\theta = 0°$ is the forward stagnation point. The sphere was supported via a rigid back spindle with a circular diameter of 19 mm and approximately 370 mm in length.

The pressure on the surface of the sphere was transmitted, via hypodermic tubings and through a scannivalve[a], to a pressure transducer. The pressure was measured as the difference between the static pressure at the surface of the sphere, Ps, and that at the plenum of chamber of the tunnel, P. The static pressure at the plenum chamber and the total pressure, H, at the contraction entry of the tunnel were measured independently by self balancing weighbeam transducers thus provided pressure references for the evaluation of pressure coefficient, Cp, as well as the free stream Mach number, M_∞. Cp was evaluated as $(Ps - P)/(\frac{1}{2}\rho v^2)$, where ρ is the density of air, and v is the air velocity. Three sets of readings were taken for each experimental condition and the results were averaged. The experimental values of M_∞, Re and Cp were then corrected for wind tunnel wall interference effects according to the methods of Garner et al (1966). The experimental uncertainties of the measured M_∞, Re and Cp were 0.2%, 0.25% and 0.5% respectively.

RESULTS AND DISCUSSIONS

The pressure distributions on the surface of the sphere are shown in the graphs of Fig. 1 as Cp versus θ. The present results at low subsonic speed ($M_\infty = 0.40$), where the compressibility of air is less significant, were compared with the previously published data of Fage (1936) and Kaplan (1940) in Fig. 1 (a) and the agreements were good.

Fig. 1 (b) to (e) show that, when the free stream Mach number was in the range $0.40 \leq M_\infty \leq 0.70$, two distinct distribution patterns were observed as Re increased through the critical range. At $Re < Re_{crit}$, where separation occurs in laminar boundary layer, minimum Cp occurred at $\theta \approx$

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[a] Registered trademark of Scannivalve Corp., San Diego, U.S.A.

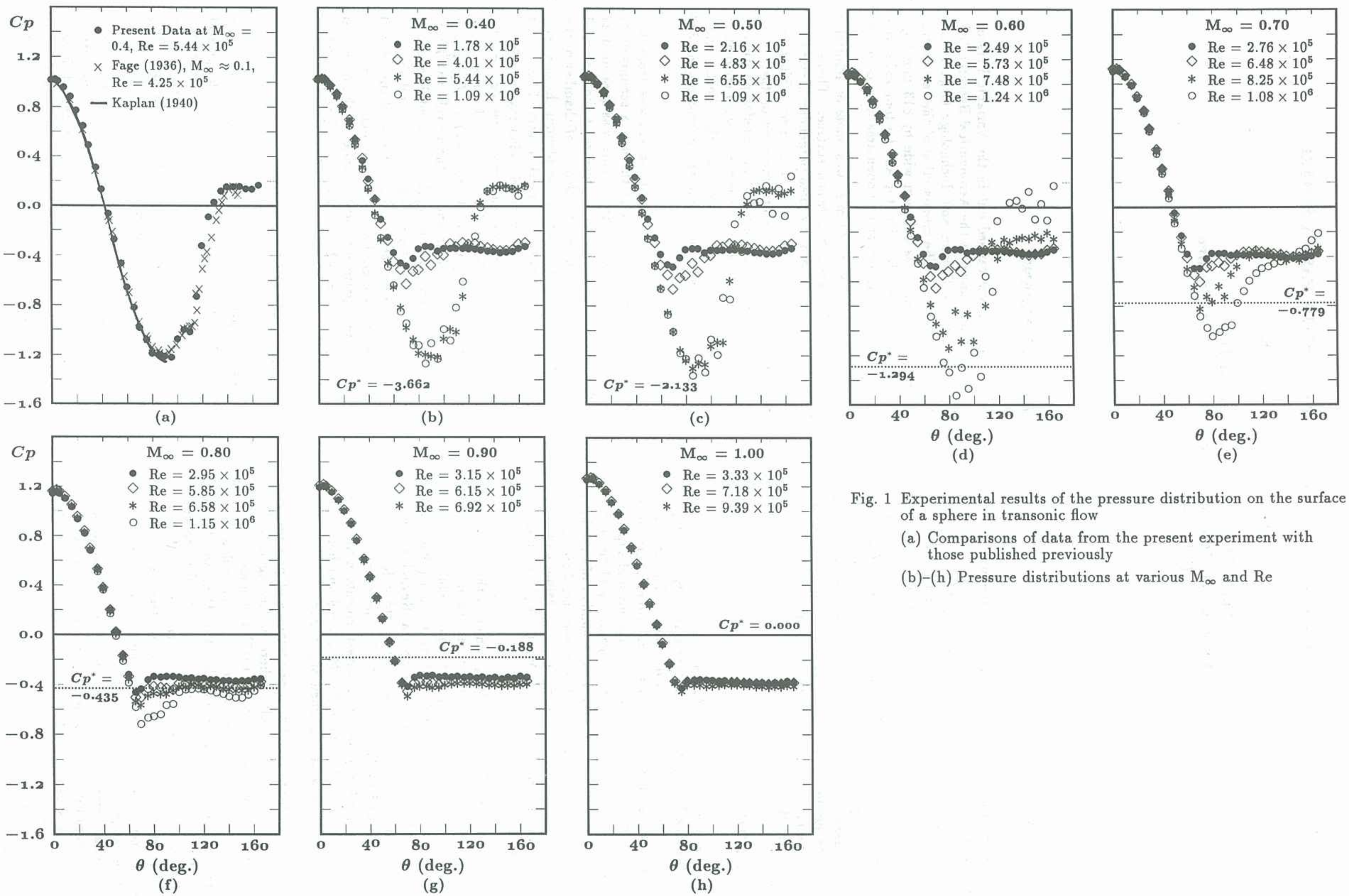


Fig. 1 Experimental results of the pressure distribution on the surface of a sphere in transonic flow

(a) Comparisons of data from the present experiment with those published previously

(b)-(h) Pressure distributions at various M_∞ and Re

70° and had a value of about -0.6 to -0.5. As Re increased towards $\mathrm{Re}_{\mathrm{crit}}$, the Cp values in the range of $50° < \theta < 100°$ decreased and showed signs of scattering. The point of separation, which can be located from the graph to be the θ at which the Cp curve begins to level off, shifted from approximately 80° to 105° as the critical range of Re was traversed. Maxworthy (1969) and Achenbach (1972) found that the laminar boundary layer separates at $\theta = 82.5°$ and 82° respectively, which was in close agreement with the present results.

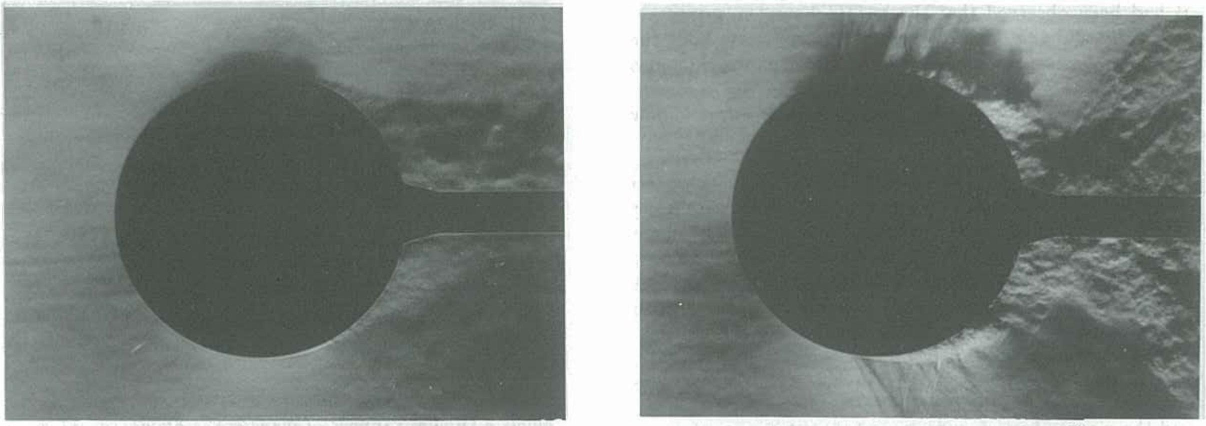
At $\mathrm{Re} > \mathrm{Re}_{\mathrm{crit}}$, where separation occurs in turbulent boundary layer, the minimum Cp was drastically reduced to approximately -1.3 at $\mathrm{M}_\infty = 0.40$ and the location of the minimum Cp had moved downstream to $\theta \approx 90°$. At $\mathrm{M}_\infty = 0.50$ the minimum Cp was further reduced to around -1.4, and was less than -1.5 at $\mathrm{M}_\infty = 0.60$. However, at $\mathrm{M}_\infty = 0.70$, the minimum Cp was approximately -1.1. That is, the minimum Cp had gone through a local minimum between $\mathrm{M}_\infty = 0.50$ and $\mathrm{M}_\infty = 0.70$. The point of separation at $\mathrm{Re} > \mathrm{Re}_{\mathrm{crit}}$ was found to be in the region of $\theta = 120°$ to 130° and had no apparent dependence in Re. Fig. 2 (a) shows a Schlieren photograph of a typical turbulent boundary layer separation when $\mathrm{Re} > \mathrm{Re}_{\mathrm{crit}}$. The point of separation was well past the $\theta = 90°$ point and a narrow wake behind the body was produced.

In laminar boundary layer separation, the Cp recovered to approximately -0.35 after the separation. This value was increased to around $+0.15$ when the separation was in the turbulent boundary layer. The free stream Mach number did not seem to have any influence on these Cp values after the boundary layer separation.

The critical range of Re was found to increase with M_∞, which was in accordance with the results of Naumann (1953). At $\mathrm{M}_\infty = 0.40$ and 0.50, $\mathrm{Re}_{\mathrm{crit}}$ was in the range of $4.0 \times 10^5 <$ to $< 6.6 \times 10^5$. At $\mathrm{M}_\infty = 0.60$, it was between 5.7×10^5 and 9.8×10^5, and at $\mathrm{M}_\infty = 0.70$, $6.5 \times 10^5 < \mathrm{Re}_{\mathrm{crit}} < 1.1 \times 10^6$. This is related to the fact that as M_∞ increases, laminar boundary layer becomes more stable and boundary layer transition occurs at a much higher Re (Braslow and Knox, 1958).

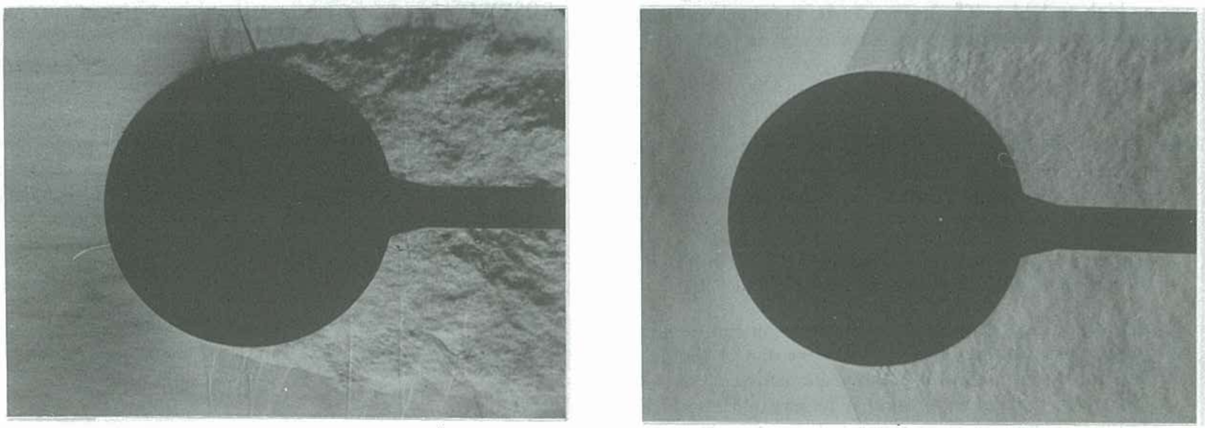
When $\mathrm{M}_\infty > \mathrm{M}_{\mathrm{crit}}$, the velocity of air on the surface of the sphere reached sonic. A supersonic pocket existed, which terminated with a shock. The shock caused a pressure jump, the magnitude of which depended on the strength of the shock, in the boundary layer. However, when the boundary layer was laminar and M_∞ was not far above $\mathrm{M}_{\mathrm{crit}}$, the flow would have separated before reaching sonic. No shock would appear under such conditions. The critical pressure coefficient, Cp^*, which is the value of Cp when the local Mach number is 1, has been evaluated for each of the M_∞ (Rosenhead et al, 1952). These values are shown in Fig. 1 (d) to (g) as dotted lines. When Cp is below Cp^*, the local Mach number is greater than 1. If Cp is above Cp^*, the local air velocity is subsonic.

Fig. 1 (d) shows that at $\mathrm{M}_\infty = 0.60$ and when $\mathrm{Re} = 7.48 \times 10^5$ the minimum Cp was close to but above Cp^* signifying that the local air velocity had not quite reached sonic. However, it should be noted that the measured Cp was an average of only three "instantaneous" values and practically no time dependent fluctuation had been taken into account. The scattering of the data around the minimum region suggested that there was significant unsteadiness in the pressure readings. A possible picture would be that there was a certain time when the local velocity at the



(a) $\mathrm{M}_\infty = 0.50$, $\mathrm{Re} = 6.55 \times 10^5$

(b) $\mathrm{M}_\infty = 0.70$, $\mathrm{Re} = 1.08 \times 10^6$



(c) $\mathrm{M}_\infty = 0.80$, $\mathrm{Re} = 6.58 \times 10^5$

(d) $\mathrm{M}_\infty = 1.00$, $\mathrm{Re} = 7.17 \times 10^5$

Fig. 2 Schlieren photographs of transonic flow past a sphere. Direction of flow is from left to right minimum Cp region had just reached sonic, a weak shock was formed which caused a pressure jump in the turbulent boundary layer. The boundary layer could not sustain the pressure rise and therefore separated from the surface. Once the boundary layer had separated, the effective shape of the sphere was streamlined and the pressure rise due to the curvature of the body surface would not be as much. This in turn slowed down the air flow near the point of separation and the velocity thus became subsonic. The shock and the accompanying pressure jump then disappeared and as a result the turbulent boundary layer re-attached to the surface of the sphere. This caused the air velocity to increase again around the minimum Cp region and once more reached the speed of sound locally. The cycle then repeated itself and it was this on and off appearance of the shock that created large disturbances and fluctuations in the surface pressure exemplified by the scattering of the Cp values at $70° < \theta < 110°$.

In addition, when M_∞ was just above the critical value of 0.573, the shock was weak and unstable, and tended to oscillate about the region where the air velocity was reaching its maximum. The numerical experiments of Pandolfi and Larocca (1989) on transonic flow about a circular cylinder have confirmed such oscillation of the shock and their results show that the oscillation is periodic.

Seddon (1967) found that the interaction of a shock and a turbulent boundary layer could generate a small separation bubble immediately after the shock. The separated flow would then re-attach to the surface of the sphere downstream of the separation bubble and at the second separation the wake would be reduced considerably. The Schlieren photograph of Fig. 2 (b) captured the re-attachment of the boundary layer and the resulting narrow wake at $M_\infty = 0.70$. The pattern, however, was time dependent. In fact, it had been observed that the re-attachment occurred periodically and that the flow was unsymmetrical about the horizontal axis of the sphere. The Schlieren photograph also shows that there were several λ-shocks occurring in succession, which is a characteristic feature in high subsonic flow (see e.g. Ackeret et al, 1947).

At $M_\infty = 0.80$, the turbulent boundary layer could no longer sustain the high pressure rise caused by the strong shock. The separation occurred at the front of the sphere even at very high Re. At $M_\infty = 0.90$ and 1.00 the shock had completely dictated the separation and the Re effect on the pressure distribution was almost indiscernible. The Schlieren photographs of Fig. 2 (c) and (d) show the patterns of the shock induced separation at $M_\infty = 0.80$ and $M_\infty = 1.00$ respectively. The shock in Fig. 2 (c) showed the classic λ-footing resulting from the interaction of a shock and the viscous boundary layer and that the separation occurred immediately behind the first shock even though Re was as high as 1.14×10^6. In Fig. 2 (d), the shock and the associated wake were quite distinct and well defined.

CONCLUSIONS

The detailed measurements of the pressure distribution on the surface of sphere in the present experiment have provided new information and data in the transonic flow range. The results showed that

1. There was an apparent increase in Re_{crit} with M_∞ in accordance with the results of Naumann (1953).
2. At $M_\infty < M_{crit}$, the pressure distribution can be distinguished into two different patterns due to the difference in the condition (laminar or turbulent) of the boundary layer at separation. The location at which laminar boundary layer separated was $\theta \approx 80°$ and that at which turbulent boundary layer separated was $\theta \approx 130°$.
3. The location at which the minimum pressure occurred increased from $\theta \approx 70°$ to $\theta \approx 90°$ when the boundary layer at separation changed from laminar to turbulent.
4. At $M_\infty > M_{crit}$, the presence of shock induced early separation of the turbulent boundary layer. However, for $M_\infty \leq 0.70$, the separated flow was observed to have re-attached to the surface of the sphere. The subsequent wake at the second separation was hence reduced.
5. At $M_\infty \geq 0.90$, the presence of a stronger shock dictated the separation of the boundary layer at $\theta \approx 80°$ whether it be laminar or turbulent. Hence there was no apparent Re effect on the pressure distribution.

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