the inner potential core length gets shorter and the recirculation sets in earlier. It is also demonstrated that a retraction of the inner injector by a distance L_R not only has a translation effect but also increases somewhat the core length and causes a transition to a recirculation regime at lower values of r_u. It is the friction at the outer injector wall, over the retraction length, although weak, that reduces the critical velocity ratio.

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Origin of Streamwise Vortices in Supersonic Jets

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Introduction

THE purpose of this study was to clarify the initial conditions necessary for the development of streamwise vortices observed in underexpanded jets.[1–4] In particular, we examined whether the Taylor–Görtler instability established in the curved shear layers of an underexpanded jet was a sufficient condition for the formation of streamwise vortices. Recent work by Arnette et al.[4] indicates that strong streamwise structures develop in underexpanded jets issuing from nozzles having no noticeable surface imperfections. To the contrary, experiments performed by Novopashin and Perepelkin[2] suggest that a necessary condition for the formation of streamwise structures is a critical roughness on the nozzle surface. We addressed this point by examining supersonic jets using controlled disturbances with and without the presence of curvature. We expect that streamwise vortices will enhance the radial transport between the jet and the surrounding fluid. Understanding this most fundamental problem will have important technological impact on applications ranging from high-speed combustion to jet noise suppression.

Several studies have reported the presence of stationary streamwise vortices in the mixing-layer region of underexpanded axisymmetric jets.[1–4] Zapryagaev and Solotchin[1] examined the azimuthal total pressure variations in a Mach 1.5 conical nozzle at a pressure ratio of 10. Their measurements revealed the presence of stationary streamwise structure in the jet mixing region between the intercept shock and the jet boundary, resulting in pressure undulations around the jet periphery that exceeded 20 psi (138 kPa). They concluded that the streamwise vortices were set up in the highly curved shear layer due to an instability of the Taylor–Görtler type. Novopashin and Perepelkin[2] described a petal structure as seen in the shear layers of underexpanded jets issuing from a conical orifice. One principal finding of the research was that the petals were anchored to disturbances within the nozzle. Scratches in the orifice near the exit as small as 5 μm could be identified with azimuthal density variations in the jet downstream. It was observed that a critical nozzle surface roughness was necessary for spatial amplification leading to measurable streamwise structure in the jet shear layers. No streamwise structures were observed when the nozzle was sufficiently clean.

Krothapalli et al.[3] demonstrated that stationary streamwise structures are not limited to highly underexpanded jets, indicating that strong shear layer curvature is not a prerequisite for the phenomenon. Similar to the measurements of Zapryagaev and Solotchin[1] made at much higher pressure ratios, they documented total pressure variations on the order of 20 psi. More recent studies by King et al.[5] and Island et al.[6] indicate that fine surface imperfections are responsible for exciting streamwise structures in ideally expanded flows. However, an investigation by Arnette et al.[4] covering a wide range of operating conditions and nozzle types observed stationary streamwise structure in underexpanded jets but did not report any organized three-dimensionality at overexpanded or ideally expanded conditions. They concluded that the azimuthal variations were associated with streamwise counter-rotating vortex pairs that were amplified by a Taylor–Görtler instability in the curved shear layer, similar to the mechanism proposed earlier by Zapryagaev and Solotchin. Furthermore, the nozzles were described as free of imperfections, and hence no correlation was found between the shear layer dynamics and disturbances in the nozzle itself.

Results and Discussion

The present measurements were made in a blowdown jet facility having a total storage volume of 9.5 m^3 and supplied with compressed air at 140 bar. The experiments conducted at underexpanded flow conditions were performed using a fifth-order polynomial convergent nozzle having an exit diameter of 22.6 mm. Ideally expanded flow conditions were examined using a nozzle designed with the method of characteristics for flow at Mach 1.8 and having an exit diameter of 27.1 mm. A quantitative measure of the streamwise structure in the jet was made using a total head probe mounted on a computer-controlled, three-dimensional traversing system. Pressure data at each azimuthal station were averaged over a period of 0.6 s and collected in 2-deg increments. Estimates of the uncertainty in pressure were evaluated using precision error based on timewise measurements and the bias error of the Validyne pressure transducer and 16-bit analog-to-digital converter. Uncertainties in pressures were estimated at ± 0.5 psig, which corresponds roughly to the size of the symbols used in the figures. Further details of the facility can be found in Ref. 7.

Anticipating that strong streamwise structure would be more likely observed in an underexpanded jet, we started our investigation in the convergent nozzle operated at a pressure ratio of 5.1. Azimuthal pressure profiles taken at the axial locations of $x/D = 1.7$ and 2.5 are shown in Fig. 1, where D is the nozzle exit diameter. Small pressure undulations having peak-to-peak amplitudes from 2 to 5 psi can be observed around the entire jet periphery. These variations could be reproduced precisely between runs taken over a

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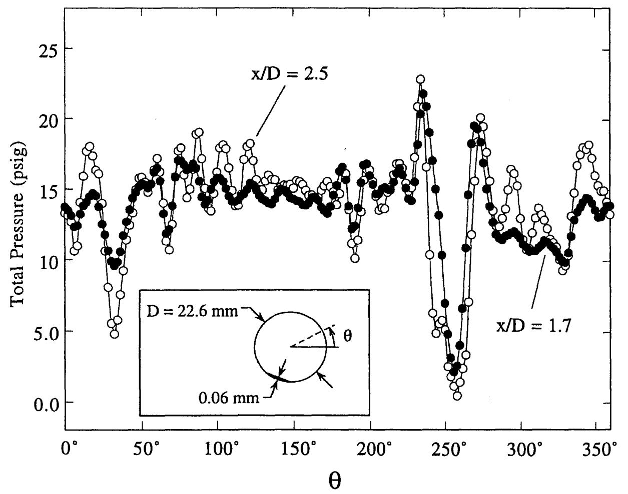

Fig. 1 Azimuthal total pressure profile in an underexpanded jet at a pressure ratio of 5.1. Data were obtained at x/D = 1.7 (r/D = 0.6) and 2.5 (0.55). Inset shows the location of a small disturbance located on nozzle lip.

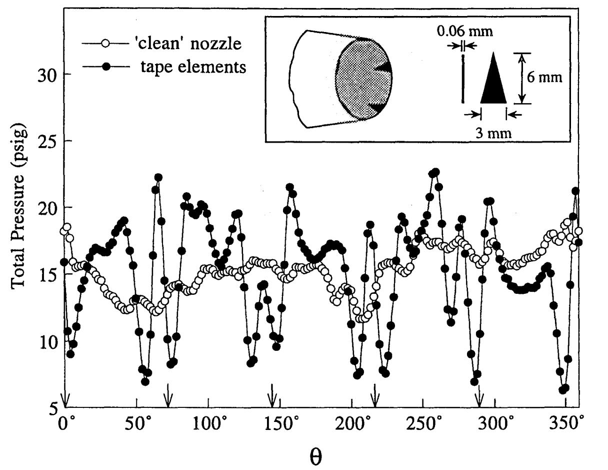

Fig. 2 Azimuthal total pressure profiles in an underexpanded jet at a pressure ratio of 5.1 with and without tape element inserts; arrows along the abscissa indicate the tape placement. Data were taken at x/D = 1.7 and r/D = 0.6. Inset shows details of the tape elements and their placement in the nozzle.

time period of several days and are not the consequence of data sampling period or experimental uncertainty. We observed a rather large excursion in the pressure at a position of $\theta = 256$ deg having a magnitude on the order (≈ 20 psi) reported in the earlier studies.[3,4] The remarkable correlation of the structures in the streamwise direction can be seen by comparing the azimuthal pressure surveys conducted at the two streamwise locations. As can be seen in Fig. 1, the detail of the undulations is virtually unchanged over a streamwise distance of almost one jet diameter. In many cases the peak-to-peak pressure variations observed at $x/D = 2.5$ are significantly larger than those at $x/D = 1.7$, indicating some streamwise amplification, as was observed by Arnette et al.[4]

The results in Fig. 1 indicate the presence of stationary streamwise structure in the jet. However, the reproducibility of the profile in almost every detail between runs taken several days apart strongly suggests that the perturbations are anchored by the facility and are not solely due to an inherent instability of the shear layer. This hypothesis was easily verified by rotating the nozzle in a fashion first proposed by Novopashin and Perepelkin[2] and observing a corresponding rotation in the azimuthal pressure profile. Encouraged by the connection between the flow response and the nozzle, which felt smooth to the touch, we removed the nozzle and carefully measured the surface on a lathe with a 0.0001-in. (0.0025-mm)-resolution surface micrometer. Around the nozzle we observed small surface irregularities having peak-to-peak heights less than ≈ 0.0005 in. (0.013 mm), which can be expected under normal machining operations. However, near the location where the large pressure excursion was measured, we found a small flat spot on the nozzle lip that had a height of 0.0025 in. (0.06 mm), as shown in the inset to Fig. 1.

To examine the role of initial conditions further, we remachined the inner surface near the nozzle exit over a streamwise distance of $D/4$ and remeasured the pressure profile under conditions nominally identical to those in Fig. 1. The profile labeled "clean" in Fig. 2 shows the pressure variations after the remachining. Undulations having amplitudes less than 5 psi were still observed and could be correlated in many instances to those recorded before the nozzle was cleaned. The inability to remove the disturbances completely is a reflection of the fact that some imperfections remain after the remachining and others probably exist upstream of $D/4$ where the machining occurred. In any event, the large disturbance at $\theta = 256$ deg was removed, and its effect on the flow is clearly absent in Fig. 2.

If disturbances as small as $k = 0.0025$ in. (0.06 mm), where k is the height of the protuberance, can cause pressure disturbances as large as 20 psi, it seemed reasonable that small artificial disturbances may be used to trigger streamwise structure as well. To test this idea, we decided to mount triangular elements along the inner surface near the nozzle exit. Five elements, each having dimensions as shown in the inset to Fig. 2, were positioned around the jet periphery and pointed into the flow. The triangles were cut from 3M Scotch™ tape having a thickness of 0.0025 in. (0.06 mm). The pressure profile taken in the presence of the tape elements is shown in Fig. 2. The pressure excursions are quite dramatic and display a characteristic W shape at the positions where the tape elements were located in the nozzle, presumably due to the counter-rotating structure that is triggered by the boundary-layer disturbance.

Time-integrated laser sheet images (30 pulses of ~10-ns duration taken over a period of 6 s) of the jet diametral plane in Fig. 3 reinforce the pressure measurements. In the absence of artificial disturbances (Fig. 3a), a characteristic ring is observed that indicates that the small-amplitude pressure variations measured in the clean nozzle in Fig. 2 do not play any significant role in the three-dimensional jet development at least up to the streamwise distance of $x/D = 1.7$. However, the photograph taken with the tape elements (Fig. 3b) demonstrates how influential even small perturbations in the nozzle boundary layer can be in determining the three-dimensional flow evolution.

These results strongly suggest that streamwise structures originate in the disturbance field of the separating boundary layer but do not indicate whether shear layer curvature is necessary for their subsequent amplification downstream. This question was addressed by introducing triangular tape elements into the boundary layer of an ideally expanded jet at Mach 1.8. Total pressure variations in the shear layers of the ideally expanded jet without tape elements were consistently less than 5 psi but increased to over 20 psi in the presence of the tape elements. Profile details (not shown here; see Ref. 5) are somewhat different from those observed in the underexpanded jet observed in Fig. 2. In particular, only a weak W structure was observed in the ideally expanded jet. This is most likely the consequence of the lower amplification rates of the relatively straight shear layer of the ideally expanded jet compared with the curved shear layer at underexpanded pressure ratios.

To further explore the connection between the nature of the boundary-layer disturbances and the flow evolution downstream, a preliminary study was made of the geometry of the tape elements. Triangular elements were again cut from Scotch tape with a fixed base-to-peak height of 6 mm but with variable apex angles α from 20 to 90 deg. The tape elements (six total) were placed symmetrically in a Mach 1.8 nozzle operated at its design pressure ratio. To evaluate the impact of tape geometry on the global flow evolution, a pitot probe was positioned on the jet centerline downstream of the potential core at $x/D = 15$ to obtain the local Mach number. In the absence of tape elements, i.e., a clean nozzle, the normalized Mach number on the jet centerline at $x/D = 15$ was $M/M_o = 0.77$, where M_o is the Mach number in the jet exit plane. As the results of Fig. 4 indicate, jet mixing is significantly influenced by the apex angle of the tape, with an angle of $\alpha = 25$ deg leading to maximum mixing in the jet, as indicated by a 7% reduction in the local Mach number.

Also shown in Fig. 4 is the centerline Mach number obtained when six rectangular tape elements are used and oriented with their

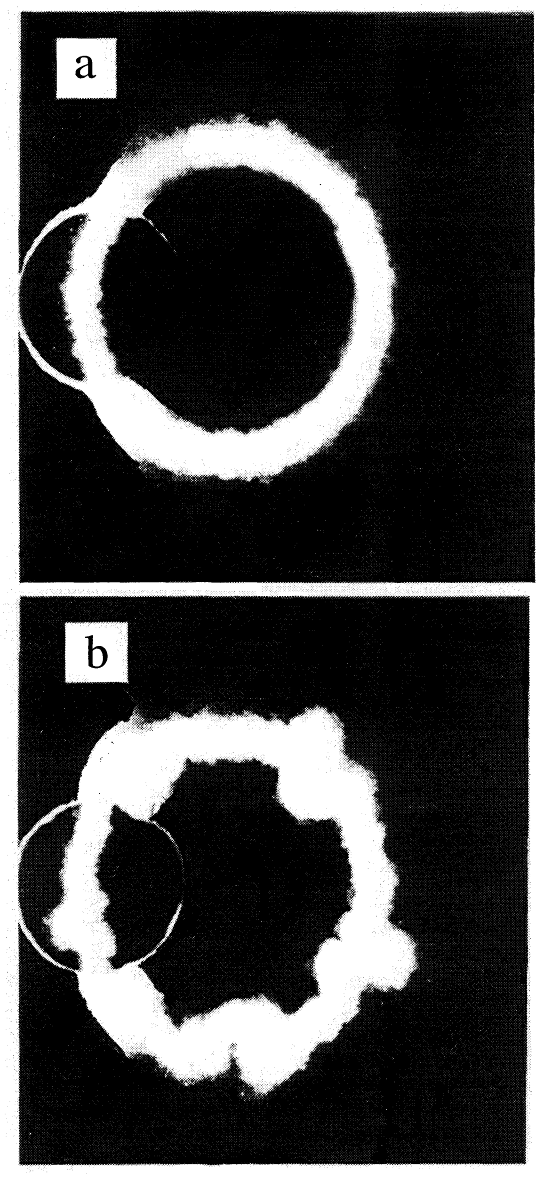

Fig. 3 **Laser sheet flow visualization of the mixing region in an underexpanded jet at a pressure ratio of 5.1 at $x/D = 1.7$: a) clean nozzle and b) nozzle with five tape elements positioned near the nozzle exit.**

long dimension aligned with the flow. Clearly the oblique nature of the tape element is critical for producing a disturbance that is amplified in the boundary layer and shear layer regions of the jet. Because the triangular-shaped tape elements lead to significant flow disturbances but the rectangular ones do not, it is likely that the streamwise vorticity produced by the delta elements is key to subsequent amplification downstream. Consequently, the presence of any arbitrary bump on the nozzle surface may not lead to significant changes in the jet development.

The measurements obtained in the ideally expanded jet at Mach 1.8 clearly show that shear layer curvature is neither a necessary nor a sufficient condition for the amplification of streamwise structure in supersonic jets. The spatial amplification of three-dimensional disturbances in the shear layer will depend on a number of factors in addition to streamwise curvature, including effects of density ratio, velocity ratio, and convective Mach number. Consequently, a Taylor–Görtler instability may accentuate the spatial amplification process but is not required per se. More importantly, the present results indicate that stationary streamwise vortices can be established only if the natural amplification process is accelerated by a finite amplitude three-dimensional input. It appears that the three-dimensional disturbances residing in the boundary layers of relatively clean laboratory nozzles are not of sufficient magnitude or spectral character to trigger the formation of streamwise vortices.

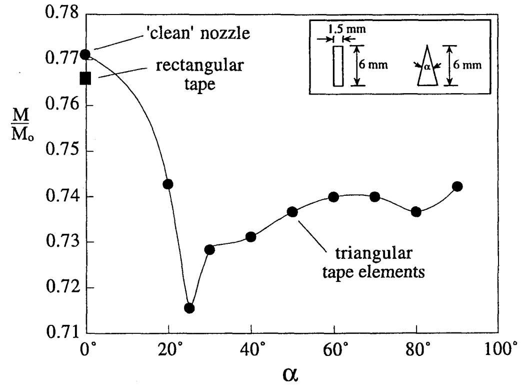

Fig. 4 **Variation of the normalized centerline Mach number at $x/D = 15$ with apex angle of the triangular tape elements; the jet responses without tape elements and with rectangular tape elements are also shown.**

We can now speculate why streamwise vortices have been observed in other laboratories in what have been described as nozzles with no noticeable surface imperfections.[4] Novopashin and Perepelkin[2] found that scratches as small as $k = 5\ \mu m$ could trigger streamwise structure in the jet downstream; however, their jet diameters were quite small, varying between 0.5 and 4 mm. For the largest diameter reported, 4 mm, the scratch of 5 μm was not of sufficient magnitude to trigger azimuthal density variations downstream. They concluded that a critical k/D of at least 0.0013 was necessary to form a petal structure in the jet. In our experiments the tape thickness provides a k/D slightly greater than 0.002, which should be quite sufficient to trigger streamwise structure based on their criterion. Arnette et al.[4] stated that their nozzles were free of imperfections; however, for the diameters used in that study a critical $k/D \approx 0.0013$ would correspond to a roughness height on the order $k \approx 0.0006$ in. (0.015 mm), which is probably too small to detect without special equipment.

Conclusions

The aim of this study was to shed some light on the origins of the streamwise structures observed in supersonic jets. Particular interest was paid to the role of nozzle imperfections and streamwise curvature of the shear layer. The results suggest that, although streamwise curvature may increase the spatial amplification rate of three-dimensionalities, it is not essential for their development. A complementary objective was to examine the influence of artificial low-profile disturbances placed in the nozzle boundary layer. It was shown that oblique disturbances created by triangular-shaped tape elements were effective at disturbing the shear layers and jet development downstream, whereas rectangular elements were quite ineffective. This suggests that disturbances that introduce streamwise vorticity into the boundary layer are more readily amplified by the inherent instability of the jet shear layers. It is fair to state that we have not measured streamwise vorticity and hence cannot provide more than circumstantial evidence of its presence. However, we believe that we have shown a strong correlation between disturbances originating in the nozzle boundary layer and the presence of stationary streamwise structure in the shear layer downstream.

In addition to obtaining a more complete physical understanding of the problem, we should ask ourselves how this information could be applied to the development of more sophisticated shear flow control schemes. In particular, the low profile of the tape elements suggests that they will have a very low thrust penalty while providing an efficient mechanism to enhance jet mixing. The critical height of the disturbance necessary to trigger the formation of streamwise vortices is quite small. Estimates of the nozzle exit boundary-layer displacement thickness δ^* in the ideally expanded jet of the present study indicate that a value of k as small as $\delta^*/12$ is sufficient for tripping purposes.

Acknowledgments

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Effect of Heating on Quiet Flow in a Mach 4 Ludwieg Tube

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Introduction

HIGH-SPEED, quiet-flow wind tunnels are needed for the study of boundary-layer transition to allow measurements under low-noise conditions comparable to flight.[1,2] Conventional facilities suffer from turbulent boundary layers on the nozzle walls. They radiate high levels of sound, which can dominate transition on the model.[3] Quiet-flow facilities maintain laminar boundary layers on the nozzle walls to provide freestream fluctuation levels of approximately 0.1% or less; these fluctuation levels are an order of magnitude less than those in conventional facilities and are comparable to flight measurements.[4] A low-Reynolds-number, Mach 4, quiet-flow Ludwieg tube was previously developed at Purdue University to achieve quiet flow at lower cost.[5] Reference 5 shows that pitot pressure fluctuations normalized by the mean pitot pressure are about 0.06% under conditions when noise radiated from turbulent spots on the nozzle walls is present about 1% of the time. This noise level was used as the criterion for quiet flow and corresponds to static pressure fluctuation levels that are also about 0.06% (Ref. 6).

A high-Reynolds-number, Mach 6, quiet-flow Ludwieg tube is now being built.[7] To reach Mach 6, the stagnation temperature must be raised by heating the driver tube and the air it contains. This raised two main issues. 1) Would free-convection currents be unavoidable in the driver tube, and would these be swept into the test section, possibly eliminating quiet flow? 2) What effects will the heated gas have on the instability of the nozzle wall boundary layer and therefore on the extent of the quiet flow?

The first issue has never been addressed before. The Gottingen hypersonic Ludwieg tube operates with a heated driver tube, but the conventional design results in pitot pressure fluctuations that are 1.8% of the mean.[8]

The second issue, the effect of nonuniform wall temperature on instability and transition, has been addressed many times.[9–12] Uniform cooling stabilizes low-speed airflow as well as the low-Mach-number first-mode waves; stabilization is also observed for localized heating when it is carried out upstream of the onset of instability. This is because the wall now looks cold to the preheated boundary-layer gas. Heating also thickens the boundary layer and thus reduces the effectiveness of the surface roughness. Harvey et al.[13] heated an early Mach 5, axisymmetric, quiet-tunnel nozzle by 40% above the total temperature and showed that transition was delayed by 19%. Demetriades[14] also reported a delay of transition using localized heating near the nozzle throat.

This Note reports measurements of quiet-flow extent carried out in the Purdue University Mach 4 Ludwieg tube with a heated driver tube. The facility, instrumentation, and notation are described in Ref. 5. Pitot pressure measurements were made with a fast-response pressure transducer located on the centerline. Temperature measurements were also made using a tungsten cold wire that was 3.8 μ in diameter and 0.5 mm long.[15] The measurements were recorded at 250 kHz with an eight-bit digital oscilloscope for 1 s.

Results

Figure 1 shows typical records for an unheated run. The stagnation pressure upstream of the pitot shock was inferred from the normal shock conditions. The recovery factor was taken as 1.11 for the cold-wire measurement, based on the hot-wire Reynolds number of 4.8 and Knudsen number of 1.2 (Ref. 16). The pressure and temperature decay with time as the flow exits the driver tube. An expansion wave reflects back and forth inside the driver tube during the run. When the expansion wave reflects from the contraction, the test section pressure suddenly drops. During the 122-ms intervals, the flow is quasisteady because the pressure drops only about 2% and the temperature drops 0.4%.

Pitot pressure statistics were computed for 80-ms intervals located in the middle of the 122-ms quasisteady periods. Figure 2 shows the rms pitot fluctuations divided by the mean pitot pressure for each such segment. The pitot probe was located on the tunnel centerline at $z = 33.86 \pm 0.16$ cm for the present measurements and at $z = 33.17$ cm for the measurements replotted from Ref. 5. Here, unlike in Ref. 5, $z = 0$ at the nozzle throat. Uniform flow begins at $z = 23.70$ cm, and so the probe is 10.16 cm downstream of the onset of uniform flow. The pitot fluctuations remain below the quiet-flow criterion of 0.06% of the mean[5] for stagnation pressures below about 90 kPa. This is true for all of the segments, not just for the first 122 ms until the first reflection of the expansion wave.[17] This allows measurement in an extended duration of quiet flow, during which

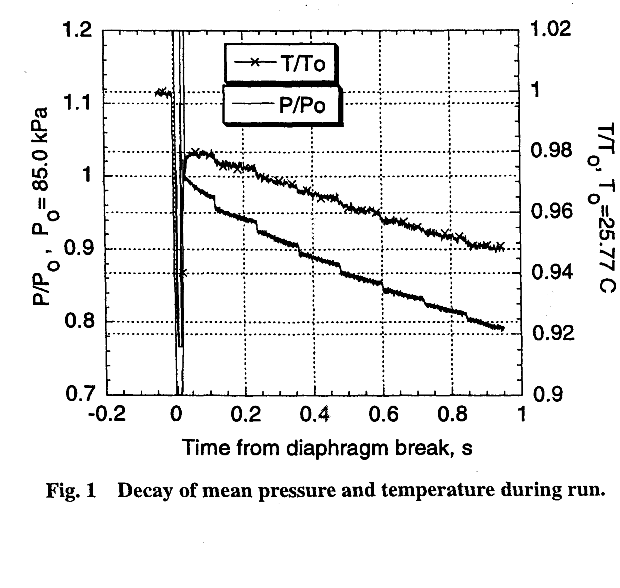

Fig. 1 Decay of mean pressure and temperature during run.

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