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by

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SLR TEMPERATURE MEASUREMENTS IN THE SUPERSONIC EXPANSION OF NITROGEN IN A SHOCK-TUNNEL

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SUMMARY

Temperature measurements, using the SLR method, are presented for the expansion of nitrogen in nozzles attached to a shock-tube. The measurements were made at an area ratio of 8.5 in a two-dimensional nozzle and at an area ratio of 152 in a conical nozzle. Initial conditions were such that at the entrance to the nozzles the temperature ranged between about 2500 K and 5300 K and the pressure between 1 atmosphere and 30 atmospheres.

Temporal variations of temperature were found in the nozzle flow which are similar to those previously measured at the nozzle entrance.

The apparent de-excitation rate of the nitrogen vibrational mode is up to 100 times faster than shock excitation data suggest.

*Replaces A.R.C.34 951

Contents

1. Introduction

The interest in hypersonic aerodynamics occasioned by the practicability of spaceflight has necessitated the construction of experimental facilities capable of simulating the flight conditions in one or more respects. One of the more important of these conditions is the very high total specific enthalpy associated with atmospheric flight at very high speeds. The correspondingly high temperatures, well above the melting points of structural materials, have led to the development of wind-tunnels in which the high enthalpy flow is of very short duration, so that only a minimum amount of heat transfer takes place to the structure of the tunnel. Among these devices is the reflected-shock tunnel, in which a convergent-divergent nozzle is fed from a reservoir of high enthalpy gas generated by the passage of a normal shock-wave and its reflection from the end wall of a shock-tube.

The ideal behaviour of such a tunnel is fairly well understood (see, for example, Glass & Hall, 1959). However in practice departures from this ideal behaviour arise as a result of "real-gas effects"; viscous friction, heat transfer, turbulent mixing and deviations from thermal equilibrium at the molecular level all play a part.* Many of these effects have been investigated both experimentally and theoretically, and while they are thought to be understood in large measure, the complexity of the flow processes has meant that accurate predictions of the state and duration of the flow of test gas cannot be made. In essence then, each shock-tunnel needs to be calibrated. Of course this is true of any wind tunnel, but the high specific enthalpy of the shock-tunnel flow, the way in which this flow is generated and its short duration make the calibration more difficult than with conventional wind-tunnels.

An earlier report (Lewis & Bernstein, 1973) described some experiments designed to ascertain the thermodynamic state and steadiness of the reservoir gas behind the reflected shock in the small shock tube at Queen Mary College, the cross-section of which is 38.1 mm square.

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* Caloric and thermal imperfections may be readily taken into account and are not regarded as affecting the "ideal" behaviour, a term used to denote the behaviour under conditions when transport phenomena depending upon molecular collisions are negligible.

The results showed that the reservoir gas was not in as uniform a thermodynamic state as is desirable, nor is it free of disturbances for as long as ideal theory predicts. Similar results have been reported by other workers (for example Lapworth & Townsend, 1967).

The present report describes some experiments designed to examine the effects of this lack of ideality on the hypersonic flow issuing from a convergent-divergent nozzle. Two different nozzles have been tested. The first is a two-dimensional nozzle mounted within the confines of the shock-tube. This is the same nozzle described earlier (Lewis & Bernstein, 1973), the measurements then relating to the entrance region ahead of the convergence. On this occasion temperature measurements in the diverging portion are described. The second nozzle is a conical one, with provision for measuring stations at several positions along the divergence, at much larger area ratios than are available with the two-dimensional nozzle. In the event measurements were only possible at one station.

The thermodynamic behaviour of the expanding nitrogen - the test gas used - is perhaps the least well understood of the processes which take place in a shock-tunnel operating at moderate pressures. In the hot "stagnant" gas in the reservoir, the pressure is usually sufficiently high for thermodynamic equilibrium to exist. Thus the temperature associated with the vibrational excitation of the molecules is equal to that of the active modes. (We are assuming here that the specific enthalpy is not so great that dissociation occurs, but a similar argument to that which follows may be applied to chemical relaxation.) When the hot gas expands into the nozzle, the pressure, density and "temperature" fall. The fall in density implies a reduction in the rate of molecular collisions, and in consequence the mechanism whereby the temperatures associated with the vibrational and active modes become equal is less effective. The "vibrational temperature" freezes and energy remains locked in the vibrational motion of the molecules, while the internal energy of the active modes - translational and rotational - is converted into the directed kinetic energy of mass motion along the nozzle.

Now the relaxation rate has been measured for vibrational excitation of the gas behind a shock-wave. Such data were obtained in this shock-tube for nitrogen, and these compared well with those of other workers (Lewis & Bernstein, 1973). In theory, with these data and the equilibrium constant, it should be possible to estimate the value at which the vibrational temperature will "freeze" for any given reservoir conditions and nozzle. Such estimates prove to be seriously in error, the apparent relaxation rate being much faster in the expanding, de-excitation environment than one would infer from the excitation data. The reasons for this remain somewhat obscure (see Hurle, 1971 for an excellent discussion). In consequence the nozzle flow must be calibrated in the gross sense to determine the average thermodynamic state, as distinct from the possible variations with time which may exist in addition to those from point to point in the test section.

Such a calibration is presented in the following sections. In the light of the foregoing remarks, attention has been concentrated on the measurement of temperature. In particular the spectrum-line reversal technique has been used with sodium as the seed element, it being assumed that the temperature at which the sodium line-reversal takes place is that corresponding to the vibrational temperature of the nitrogen.* In discussing the results in detail, emphasis is placed upon correlating the measurements with those made in the reservoir, and it may be found convenient to have more of those results (Lewis & Bernstein, 1973) to hand than are included here.

The measured temperatures are also compared with the "frozen" vibrational temperatures predicted using a computer model of the expansion with several relaxation equations. These equations have the temperature dependence of the shock-excitation data, but contain a constant factor λ, which represents the apparent enhancement of the relaxation rate during de-excitation.

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* Resonance between the sodium electronic excitation and the 7th vibrational level of the nitrogen is believed to occur. However doubt has recently been expressed (Hurle, 1971) that the vibration energy distribution is Boltzmann-like in a nozzle flow.

2. The shock-tunnel and its operating conditions

The shock-tube used to generate the high enthalpy gas has a channel section some 4.86 m in length the bore of which is 38.1 mm square. This channel section is fabricated from bars of duralumin and seals are provided so that it may be operated at sub-atmospheric pressures, a two-stage rotary vacuum pump being used to evacuate it. The steel driver-section is 1.22 m long and has a bore of diameter 76.2 mm. The Melinex diaphragms are preloaded into a special block so as to reduce to a minimum the replacement time, and consequently the time during which the tube is open to atmosphere. Diaphragm rupture is initiated using a spring-loaded plunger. A more detailed description of the basic shock-tube and its auxiliary equipment is given by Bernstein (1963) and some of the subsequent modifications are described by Ackroyd (1964). The original shock passage detectors and their associated electronic amplifiers have been replaced by the improved equipment described by Bernstein & Goodchild (1967).

The shock-tube may be converted for use in the shock-tunnel mode in one of two ways. Between the downstream end of the shock-tube and the dump-tank, there may be placed either an extension to the shock-tube channel or a conical nozzle. The extension box has been designed as a special test section for the shock-tube, and as well as having three pairs of large diameter portholes in which windows may be mounted, it also has provision for mounting models within the shock tube flow. Such models are held in position by dovetails on the upper and lower walls of the tube, and for one of the sets of experiments described here the "model" consisted of a two-dimensional nozzle formed by two steel inserts, as shown in figure 1. Station m, where the measurements were made, is 5.386 m from the main diaphragm. The area ratio of this nozzle is small (of order 10) and so it is not necessary to provide an initial pressure difference across it to aid starting. The dump-tank, nozzle and channel are all initially at the same pressure, and the nozzle driving pressure is provided by the difference between this pressure and that behind the shock which is reflected from the entrance to the nozzle.

The conical nozzle is of steel, and the interior surface is coated with an epoxy-based paint to reduce outgassing at the relatively low initial pressure needed to ensure that the nozzle will "start".

The throat section of this nozzle is 9.53 mm in diameter and it is situated about 4.9 m from the main diaphragm. A thin Melinex diaphragm is clamped at the throat section to support the initial pressure difference between the nozzle and the channel; this diaphragm vapourises rapidly upon shock reflection. Several measuring ports are provided along the expansion cone, their positions and other relevant dimensions being shown in figure 2.

The shock-tube was operated with high pressure hydrogen driving shocks into nitrogen. The nitrogen test gas was of commercial quality, but was specifically free of oxygen. Before charging the shock tube each section was evacuated. The driver section was evacuated to a pressure below 1 torr, the channel section to a value below 0.1 torr, and the conical nozzle to a pressure of about 0.01 torr, its working pressure. As mentioned earlier the time during which the shock-tube was open to atmosphere was kept to a minimum in order to minimise the impurity level of the test gas. However no special precautions were taken to prevent the back-streaming of oil vapour from the vacuum pumps.

The other main source of impurity is associated with the temperature measuring system. However, by using sodium azide, the number of impurity atoms was minimised. The single-source, sodium line-reversal system is described in detail by Lewis & Bernstein (1973).

The range of incident shock Mach number at which tests were carried out was 4.6 to 7.6, giving nominal temperatures T_0 at the nozzle entrance between about 2500 K and 5300 K. The initial pressures in the shock tube were varied so that the pressure p_0 in the reservoir at the nozzle entrance ranged between 1 atmosphere and 30 atmospheres. The initial pressure in the channel was measured by two Wallace & Tiernan gauges covering different ranges, and the shock velocity was determined by timing the shock passage between stations a short distance upstream of the nozzle entrance using deci-microsecond chronometers. The effective shock velocity at reflection was inferred from these wave velocity measurements and the shock attenuation data of Bernstein (1963), obtained for the same shock tube.

3. Measurements in a two-dimensional nozzle

Measurements of vibrational temperature T_V were made, through flush-mounted windows, at station m which was centred downstream of the throat at a local nozzle area to throat area ratio of 8.5 . The photomultiplier signals from the line-reversal system were displayed on an oscilloscope and recorded on Polaroid film. Four typical variations of T_V with time t are shown in figures 3 and 4 together with two representative oscillograms. The size of the data points is intended to indicate the estimated uncertainty* in temperature and time, the latter being measured from the (estimated) time of arrival of the incident shock at the nozzle entrance. On the oscillogram "a" indicates an absorption of light from the calibrated background source, a filament lamp at an effective brightness temperature of $\overline{T}_L$. The arrow "e" indicates emission from the sodium seed atoms in the nitrogen test gas. S_N marks the arrival at the measuring station of the starting wave process. The nozzle entrance conditions, specified by T_o and p_o are inferred from the previous calibration of the region behind the reflected shock-wave.

Two significant points C_N and D_N are marked on each temperature history to indicate the sudden changes in T_V which occur. Temperatures T_{CN} and T_{DN} together with the corresponding times t_{CN} and t_{DN} at which they occur are defined for these points. Although these values of time for the present measurements are not directly comparable with those in the region behind the reflected shock (the former are from an Eulerian point of view, while the latter are essentially from a Lagrangian viewpoint), the similarity between the temporal variations of T_V and T_o is evident. It seems reasonable therefore to associate the temperatures T_{CN} and T_{DN} with T_C and T_D respectively, and the latter may be estimatedfrom the earlier calibration at the nozzle entrance.

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* At the higher values of the reservoir temperature range, dissociation of the nitrogen occurs absorbing large quantities of energy from the active and vibrational modes. Dissociation depletes the population of the upper vibrational energy levels which are repopulated from the lower levels. Thus dissociation effectively reduces the vibrational temperature measured by the present line-reversal method.

At a time earlier than t_{CN} a rather higher temperature is evident than would be expected from the temperature variation at the entrance to the nozzle. Two possible reasons for this may be put forward. Sodium atoms are present in this nozzle before the incident shock arrives at the entrance. When the starting waves process the gas initially at the measuring station, a temperature rise occurs which is detected by the line-reversal system. This temperature may be quite high because the shock strength increases in the converging portion of the nozzle, though of course it will attenuate in the diverging section. The net effect is uncertain and vibrational relaxation behind the shock front probably also needs to be taken into account. An alternative explanation is that the signal is "false", resulting from a scattering of light into the emission beam from the high temperature gas at the nozzle entrance. This "pre-emission" signal would be reduced as the scattered light is absorbed by the relatively cooler sodium atoms in the nozzle flow and in the boundary layer on the nozzle walls.

Davies (1965) has demonstrated that as a result of the interaction which takes place between the reflected shock and the boundary layer growing behind the incident shock, cold driver gas - hydrogen in this case - is introduced into the nozzle entrance region and thus into the nozzle. It is believed that the rapid fall in temperature after t_{DN} is the result of this cold hydrogen arriving at the measuring station.

As some indication of the duration of high enthalpy flow the times t_{CN} and t_{DN} are plotted in figure 5 as a function of the shock Mach number at the nozzle entrance. Curves for the corresponding times t_C and t_D at the nozzle entrance are also shown for comparison.

It is possible to obtain estimates of the characteristic vibrational relaxation time τ for de-excitation from these measurements. The computations of Wilson, Schofield & Lapworth (1967) indicate that within the range of reservoir conditions tested, the vibrational energy mode should be frozen upstream of the measuring station m. Thus the measured reversal temperatures which are assumed to correspond to the vibrational temperature are no direct guide to the energy content of the active modes; they represent the frozen vibrational temperature.

Theoretical estimates of this frozen vibrational temperature T_F, for a particular nozzle and given initial conditions may be obtained by solving the one-dimensional flow equations simultaneously with a rate equation for vibrational relaxation. Wilson and his colleagues (1967) have carried out such calculations for a range of reservoir conditions and a two-dimensional nozzle having a throat height r^* of 2.54 mm and slightly curved walls, the semi-angle θ_N near the throat region being about 12.5^o. They use the equation (with $\lambda = 1$)

$$\frac{\tau\, p}{\mu s\ atm} = \frac{1.1 \times 10^{-5}}{\lambda} \left(\frac{T}{K}\right)^{\frac{1}{2}} \exp\left\{\frac{154}{(T/K)^{1/3}}\right\}$$

for the relaxation time together with the Landau-Teller rate equation, where $\lambda = 1$ corresponds to the measured rates in a shock-excited environment and $\lambda = 10$ implies a rate ten times faster, on average, than those measured.

The differences between their nozzle and that used in the experiments reported here may be taken into account by means of the similarity parameter (Campbell, 1963)

$$\Lambda = \frac{r^* p_o^{\lambda}}{\tan \theta_N} \quad .$$

It is assumed that T_F is a function only of Λ and that differences in r^* and θ_N may be compensated by adjustment of the reservoir pressure p_o for a fixed value of λ.
Using the results of Wilson, Schofield and Lapworth (1967) in this way and taking $\lambda = 1$, values of T_F corresponding to the present tests have been estimated. The ratios of the measured temperatures T_{CN} and T_{DN} to those values of T_F are plotted in figure 6 as a function of the stagnation temperature T_o. The fact that all these ratios are less than unity implies that $\lambda > 1$ and that de-excitation proceeds faster than excitation measurements would suggest. The procedure was repeated with $\lambda = 10$, but the ratios of measured to estimated temperature were

still below one. Unfortunately the range of computations presented by Wilson and his co-workers is not sufficient to include $\lambda = 100$ for the experimental conditions reported here, but extrapolation suggests that de-excitation of the vibrational mode proceeds about two orders of magnitude faster in this nozzle than expected from shock-excitation measurements.

The data of other workers (see Hall & Russo, 1967) are also indicated in figure 6. Agreement between their data and that reported here would be implied were the latter to fall more or less within the shaded area. Direct comparison is not strictly justifiable because of the different correlation equation they use for the excitation data. However it is expected that differences arising from different nozzle geometries and stagnation pressures may be largely eliminated by plotting the ratio of measured to calculated temperature (Hall & Russo, 1967).

4. Measurements in a conical nozzle

Temperature measurements were also made through windows mounted in the removable inserts of station AA' of the conical nozzle. The local geometric area ratio at this station is 152. The early attempts to obtain measurements were unsuccessful, a very poor signal-to-noise ratio resulting from the thick boundary layer growing on the nozzle wall through which the light had to pass. The windows, originally almost flush with the wall, were remounted so as to extend through the boundary layer as illustrated in figure 7. With this "skimmer" technique satisfactory results were obtained, but the noise level remained fairly high, largely because the equipment needs to be operated at high sensitivity when the gas density is low. Even with the "skimmer" technique attempts to obtain measurements at station CC' in the nozzle failed because the signal-to-noise ratio was so poor. Several complementary measurements of static pressure in the nozzle were made using a Queen Mary College, type H transducer (Goodchild & Bernstein, 1972) mounted

at station B. Signals were displayed on a cathode ray oscilloscope and recorded on Polaroid film.

Some typical variations of vibrational temperature with time are shown in figures 8 to 11 together with representative oscillograms. The vertical bars on the data points indicate the uncertainty in the measurements which results largely from the noise, evident on the oscillograms. Again time is measured from the estimated time of arrival of the incident shock at the entrance to the nozzle. The nomenclature used in these figures is similar to that used for the two-dimensional nozzle with the addition of a point J_N which marks the first arrival at AA' of hot gas from the reservoir. Because very few sodium atoms are present in the nozzle prior to shock arrival, the starting wave system was not detected by the sodium line-reversal system. The abnormally high "emission" signal at the beginning of each oscillogram are almost certainly caused by scattered light. The influence of the varying conditions in the reservoir is again clear and once more the sharp fall in temperature after time t_{DN} is believed to be caused by the premature arrival of cold hydrogen at the measuring station.

A static pressure record, taken at station B is reproduced as figure 12. Because of the transducer ringing, resulting from vibration of the shock-tunnel structure, only four "reasonable" records were obtained. Although this precludes quantitative measurements from being made, the influence of the varying reservoir conditions is fairly clear, and so is the arrival of the starting shock, labelled S_N , at station B.

As an indication of the duration of the (albeit unsteady) high enthalpy flow, the times t_{CN} and t_{DN} are plotted in figure 13 as a function of the incident shock Mach number $W(X_T)$ in the shock-tube. For comparison curves for the corresponding times t_C and t_D at the nozzle entrance are also shown. The time t_{JN} at which hot gas from the reservoir first arrives at the measuring station is also shown, and may be compared with time t_{SN} , the time of arrival of the starting wave at station AA', inferred from the pressure measurements at station B.

Values for the frozen vibrational temperature T_F were calculated for this nozzle using the computer programme of Wilson, Schofield and Lapworth (1967) and the relaxation-time equation of Section 3 which is based upon a correlation of shock-excitation data (Erickson 1963) which accorded quite well with the measurements reported earlier for this shock-tube (Lewis & Bernstein, 1973). Corrections for the boundary-layer growth on the nozzle wall were made by estimating a typical value of the displacement thickness, modifying the nozzle angle accordingly and using the similarity parameter Λ as before. The corrections were small, so that a more elaborate approach was unjustified in view of the uncertainties in the measurements.

Some of the measurements have been grouped into two sets: one group is characterised by a stagnation temperature of approximately 3300 K, the other group by a common reservoir pressure of 13 atmospheres. Figures 14 and 15 show these two sets of data together with the theoretical predictions for various values of the relaxation enhancement rate parameter λ . The ratio of measured to calculated frozen vibrational temperature (for $\lambda = 1$) is also shown in figure 16.

The scatter in the data arises partly from uncertainties in the measurements in the nozzle and partly from uncertainties in the stagnation conditions. An accurate assessment of the relaxation rate in this nozzle, cannot therefore be made. It would appear from figure 14 that the effective relaxation rate diminishes with increasing reservoir pressure. On the other hand figure 15 suggests that the effective rate increases with increasing T_0, although the results at high stagnation temperature are subject to greater uncertainty because of the possibility of some dissociation having occurred in the reservoir.

For this nozzle the effective enhancement rate λ would appear to be about 20 on average. Again a direct comparison with the data correlated by Hall & Russo (1967) is not justifiable because of the different basis upon which they estimate T_F . Had their rate equation been used for the shock-excitation data, a larger value of λ would have been obtained, comparable with the value of 70 that they quote.

5. Concluding remarks

Temperature measurements using the sodium time-reversal technique have been made in nitrogen expanding quasi-steadily in two separate convergent-divergent nozzles attached to a shock-tube. These measurements were made at a geometric area ratio of 8.5 in a two-dimensional nozzle and 152 in a conical nozzle. The initial shock-tube conditions were such that at the entrance to the nozzle the pressure ranged from 1 atmosphere to 30 atmospheres and the stagnation temperature from about 2500 K to 5300 K, the system being used as a reflected shock tunnel.

The variations in measured temperature in the expanded flow follow fairly closely those measured previously at the entrance to one of the nozzles, albeit on a slightly different time scale (Lewis & Bernstein, 1973). The duration of high total-enthalpy flow is about 0.3 ms. Over this period, the measured temperature, which is associated with the vibrational temperature of the nitrogen, varies by approximately 10%. The ideal behaviour of a shock-tunnel as characterised by the "tailored-interface" mode of operation was not apparent. The variations in temperature during the "steady" flow period are thought to be due to the finite extent of the "interface" between the driver and driven gas in the shock tube (Lewis & Bernstein, 1973) so that there are always waves of finite strength reflected from the interaction between this region and the reflected shock. The premature termination of the hot flow is believed to result from the arrival at the test station of cold driver gas which also emanates from the shock-mixing region interaction. The cold gas in the boundary layer, having a momentum differing from that in the core flow is not brought to rest by the reflected shock as is required for ideal operation in the tailored-interface modes (Davies, 1965).

Further non-idealities arise in shock-tunnels operated at moderate pressures because of the finite relaxation time of the vibrational mode(s) of polyatomic molecules such as nitrogen. Usually the gas in the reservoir region of a shock-tunnel is of sufficiently high density for thermal equilibrium to exist there. Upon expansion the energy in the vibrational mode is frozen, but the frozen vibrational temperatures of nitrogen appear to be lower than shock-excitation relaxation rates would

suggest. The de-excitation rates appear to proceed about 20 to 100 times faster than the excitation rate does at the same pressure and temperature.

One suggestion which has been put forward in explanation is that as the gas departs further from equilibrium the distribution of energy in the vibrational mode becomes less Boltzmann-like. Since the sodium line-reversal technique which was used measures essentially the "temperature" of only one vibrational level, it does not give a result representative of the vibrational energy as a whole. Hurle (1971) discusses this explanation further together with the results of other workers who use different measuring techniques with similar anomalous results for nitrogen (see, for example, Russo & Watt, 1968).

Another explanation involves the effects of impurities; in particular highly mobile hydrogen atoms have been suggested as having a catalytic effect. Unless elaborate precautions are taken, the impurity level is difficult to control. Systematic tests by Russo (1966) over a range of hydrogen compound concentrations from 10^{-4} to 3×10^{-3} show little effect on the de-excitation rate except for concentrations above 10^{-3}. However Russo was careful to draw no conclusions for concentrations below 10^{-4}. In the present experiments sources of hydrogen are manifold. Hydrogen was of course used as the driver gas, and in spite of evacuation of the shock-tube prior to loading with test gas, some hydrogen will have remained. Again the mechanical vacuum pumps are a source of hydrocarbon oil vapours, which may "back-stream" into the test gas, since no "cold-trap" was used. Such hydrocarbons are readily stripped of hydrogen atoms in the high temperature environment of the doubly shock-processed gas at the entrance to the nozzle. The hydrogen bond is such that the typical characteristic dissociation temperature ($\theta_D = D/k$) is about 53 000 K, so that appreciable dissociation, 0.1% say, will occur at temperatures of about 2 000 K, at pressures of order 1 atmosphere.

The present results do not allow us to distinguish between these explanations and the reasons for the anomaly remain obscure. Until a satisfactory explanation is forthcoming, tests in hypersonic high enthalpy streams will always be attended by some uncertainty as regards the state of the undisturbed flow.

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Thanks are also extended to Dr. D. Schofield of the National Physical Laboratory who kindly used his computer programme to solve the equations for the nozzle flow.

Nomenclature

p	pressure
t	trace (real) time
t_K	time to point K (see suffices)
T	temperature
T_K	temperature at point K (see suffices)
T_V	measured vibrational temperature
$\overline{T}_L$	lamp brightness temperature
$W(X_T)$	incident shock Mach number at nozzle entrance

Suffices

o	nozzle entrance conditions
1	initial channel conditions
K	points on measured data :
	K = C, D for nozzle entrance measurements
	OR K = C_N, D_N, S_N, J_N for nozzle flow measurements
F	calculated frozen value

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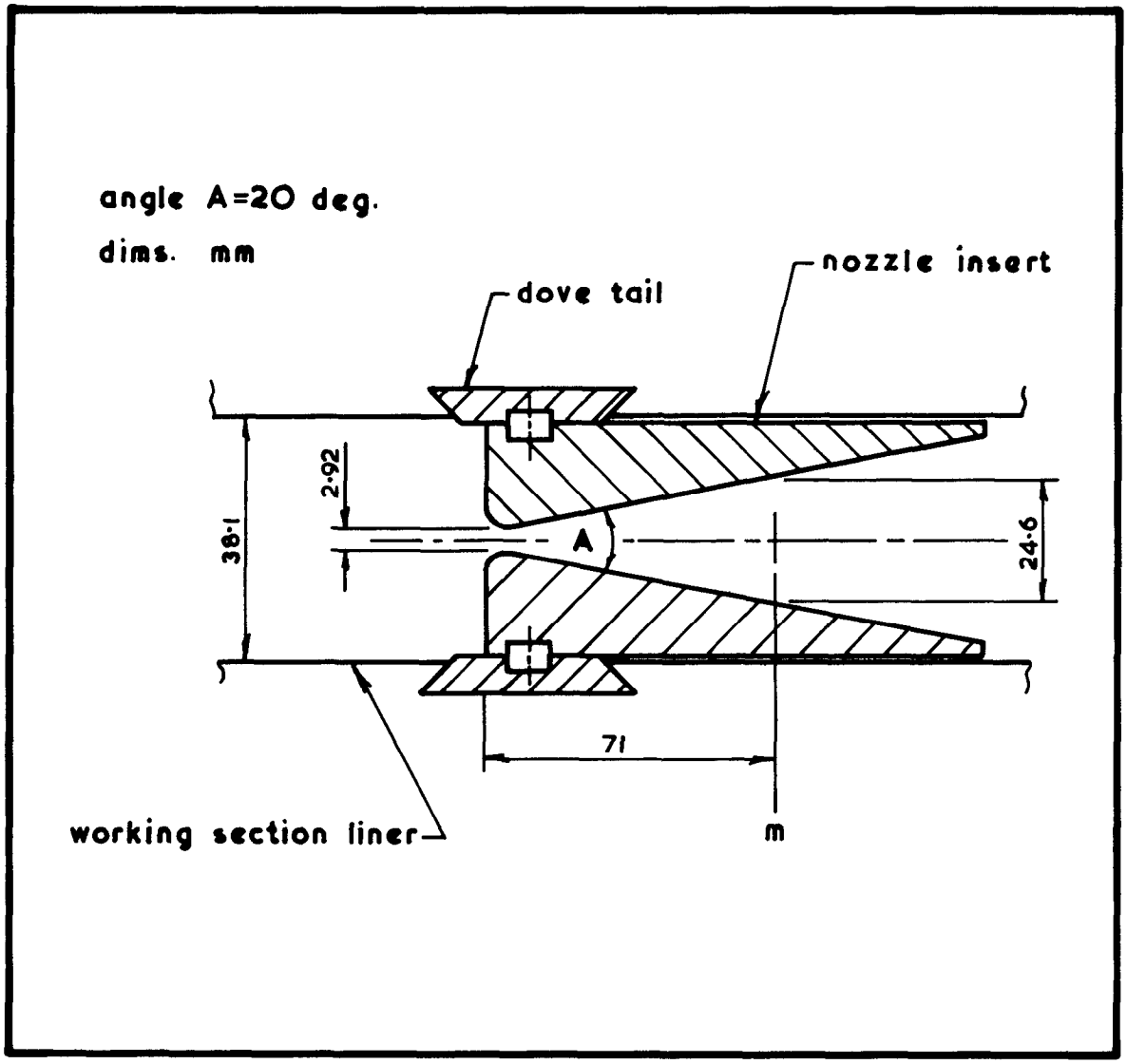


Figure 1. The two-dimensional nozzle

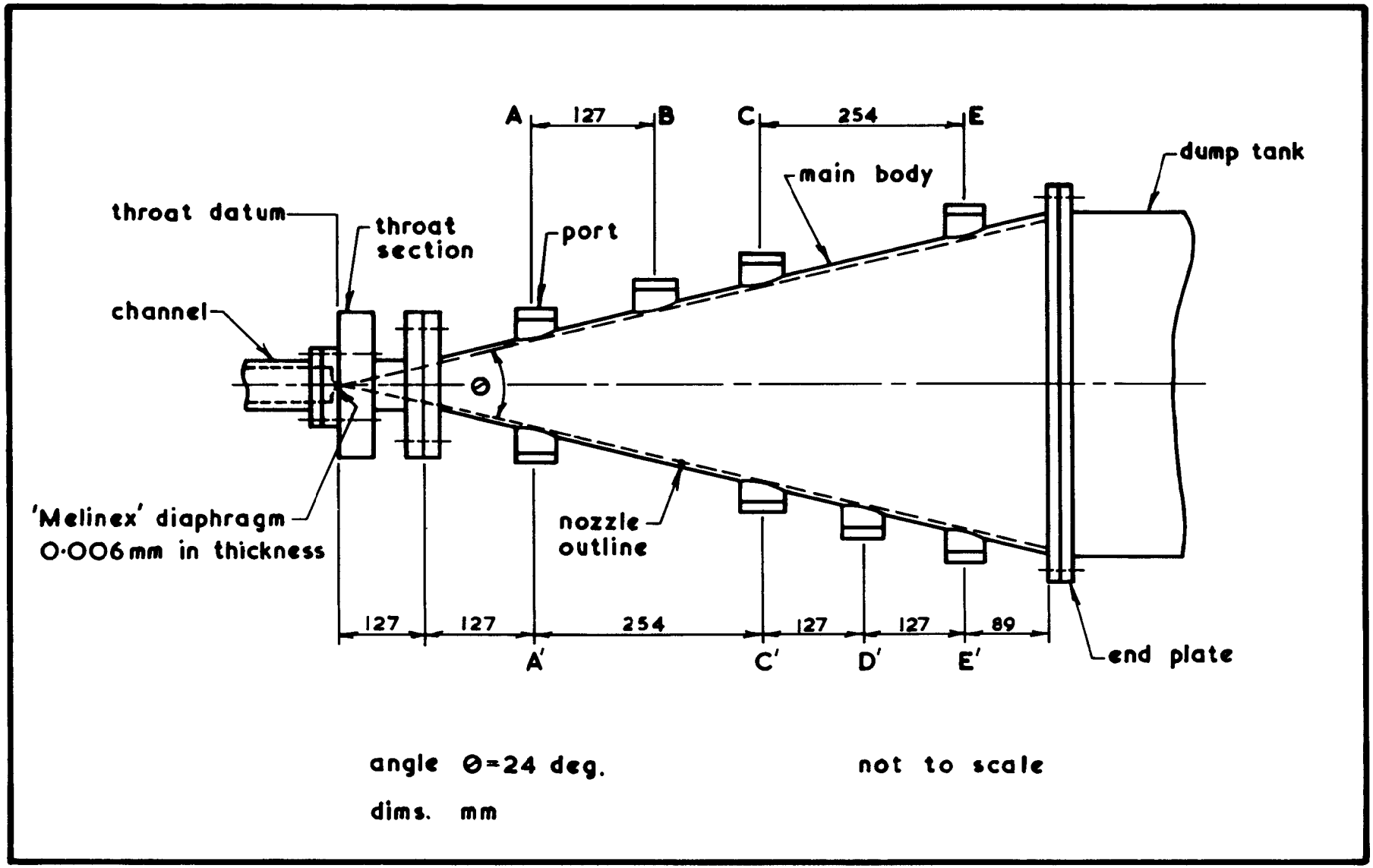


Figure 2 The conical nozzle

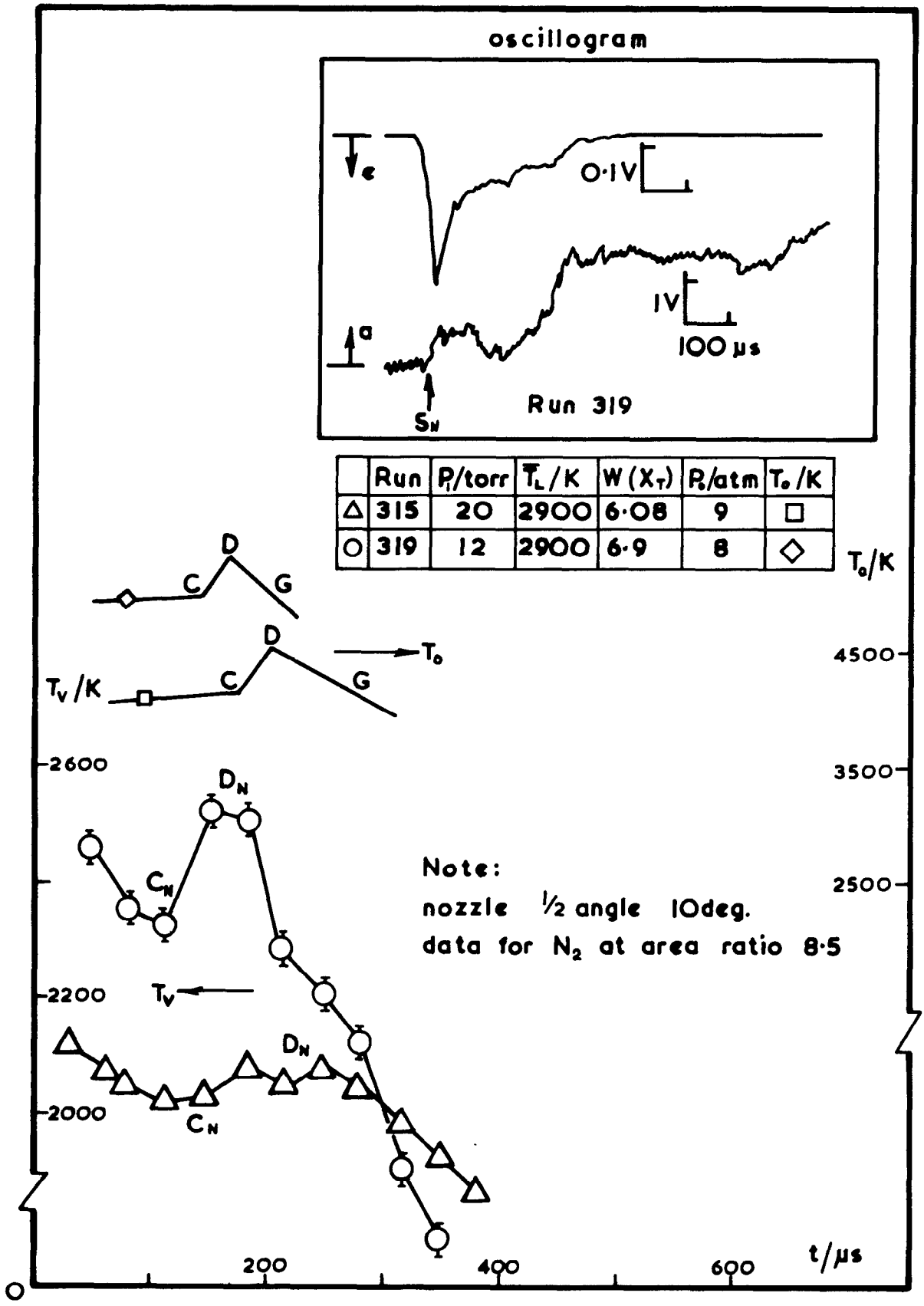
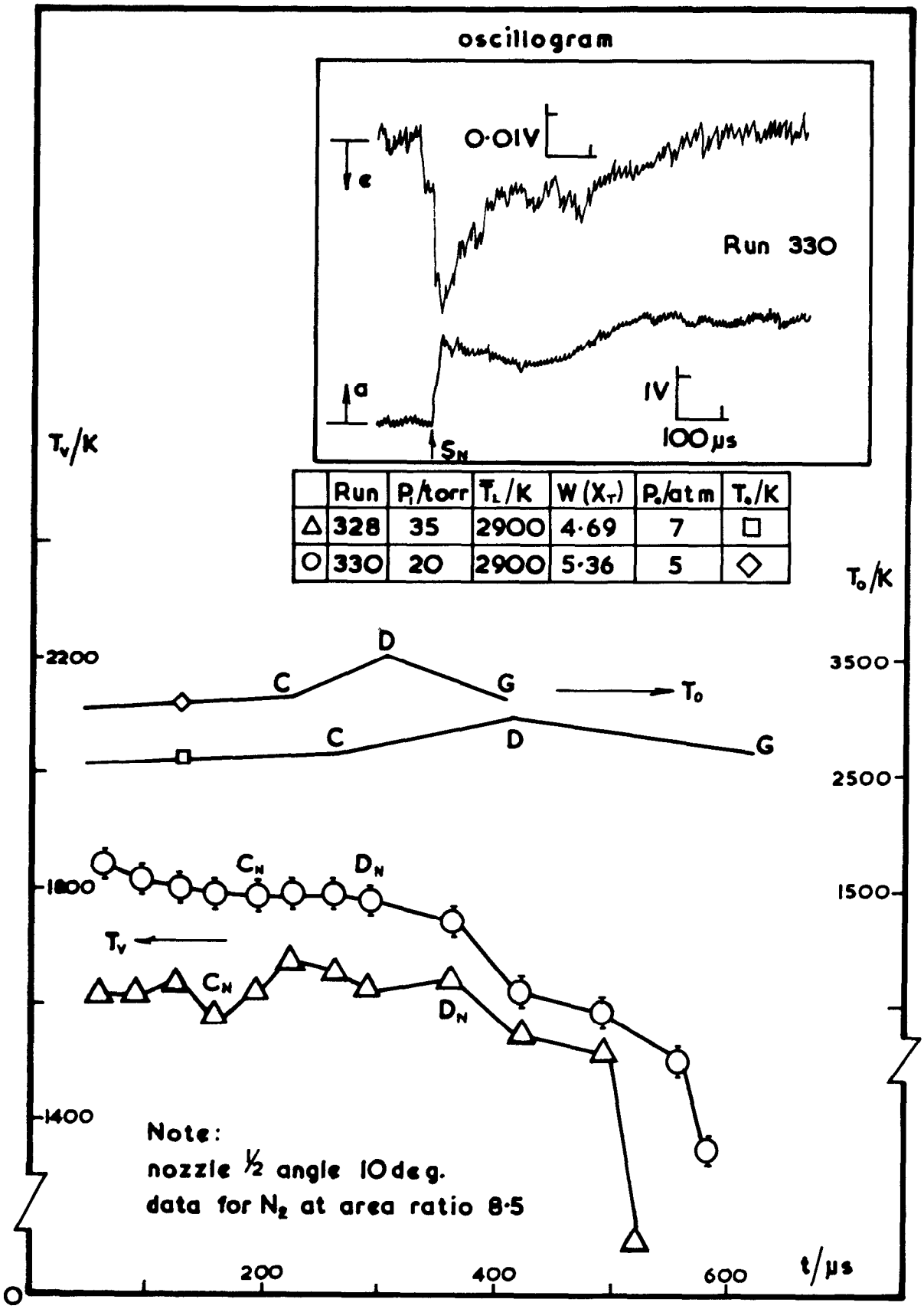


Figure 3 Vibrational temperature variation in 2D nozzle



	Run	P_i/torr	T_L/K	W (X_T)	P_0/atm	T_0/K
△	328	35	2900	4·69	7	□
○	330	20	2900	5·36	5	◇

Figure 4 Vibrational temperature variation in 2D nozzle

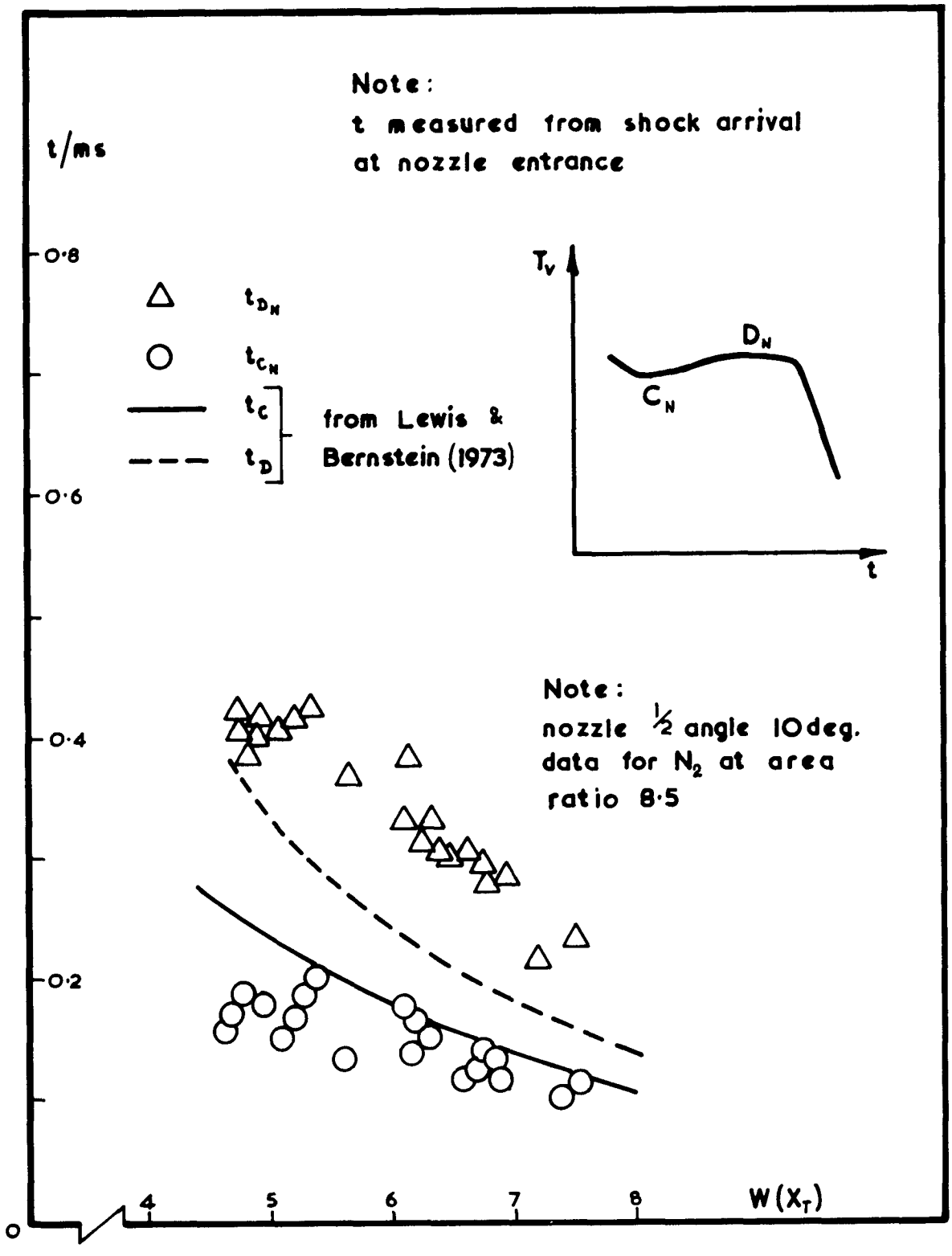


Figure 5 High temperature duration in 2D nozzle

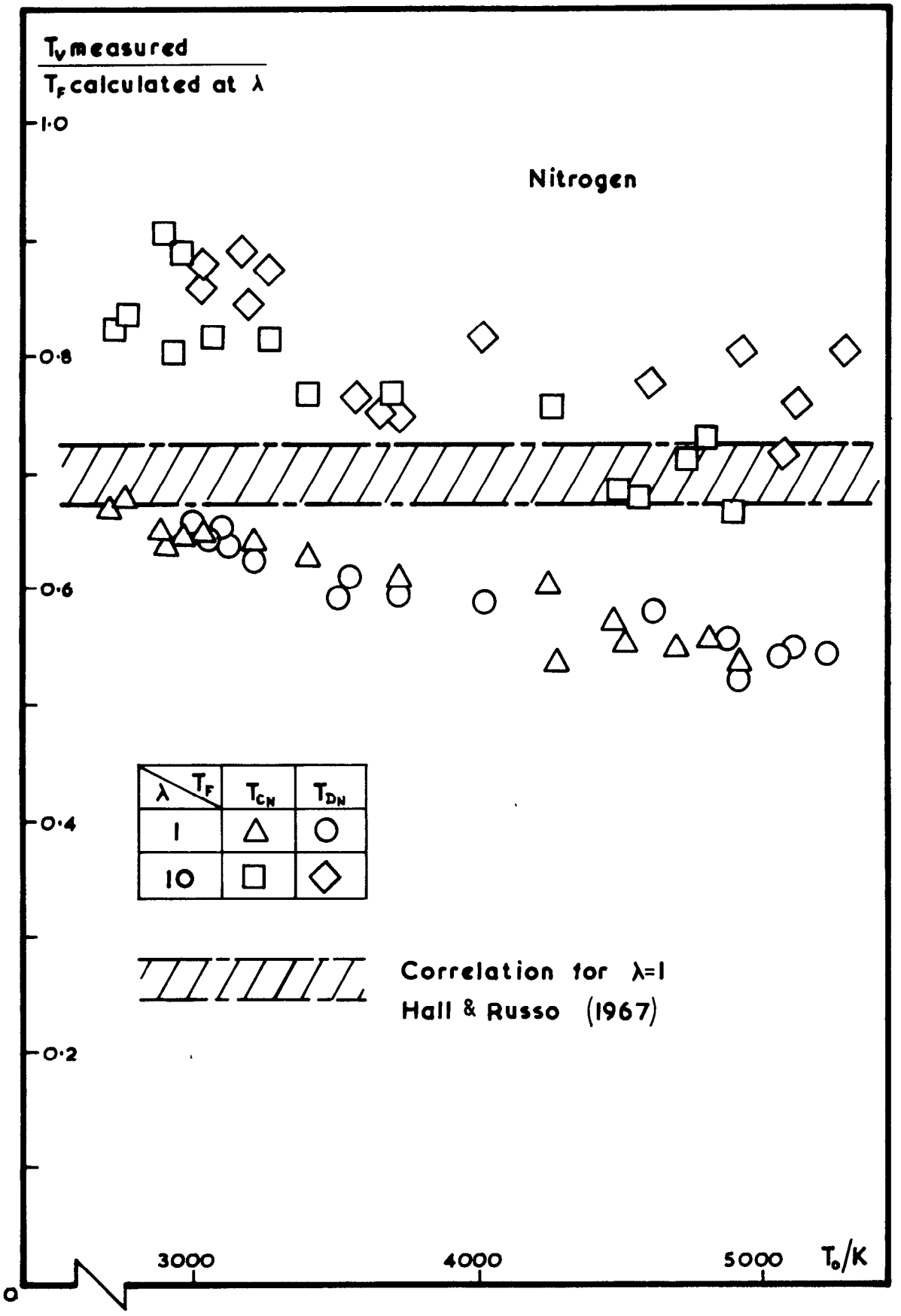


Figure 6 Measured vibrational temperatures compared with calculated frozen temperatures for two-dimensional nozzle

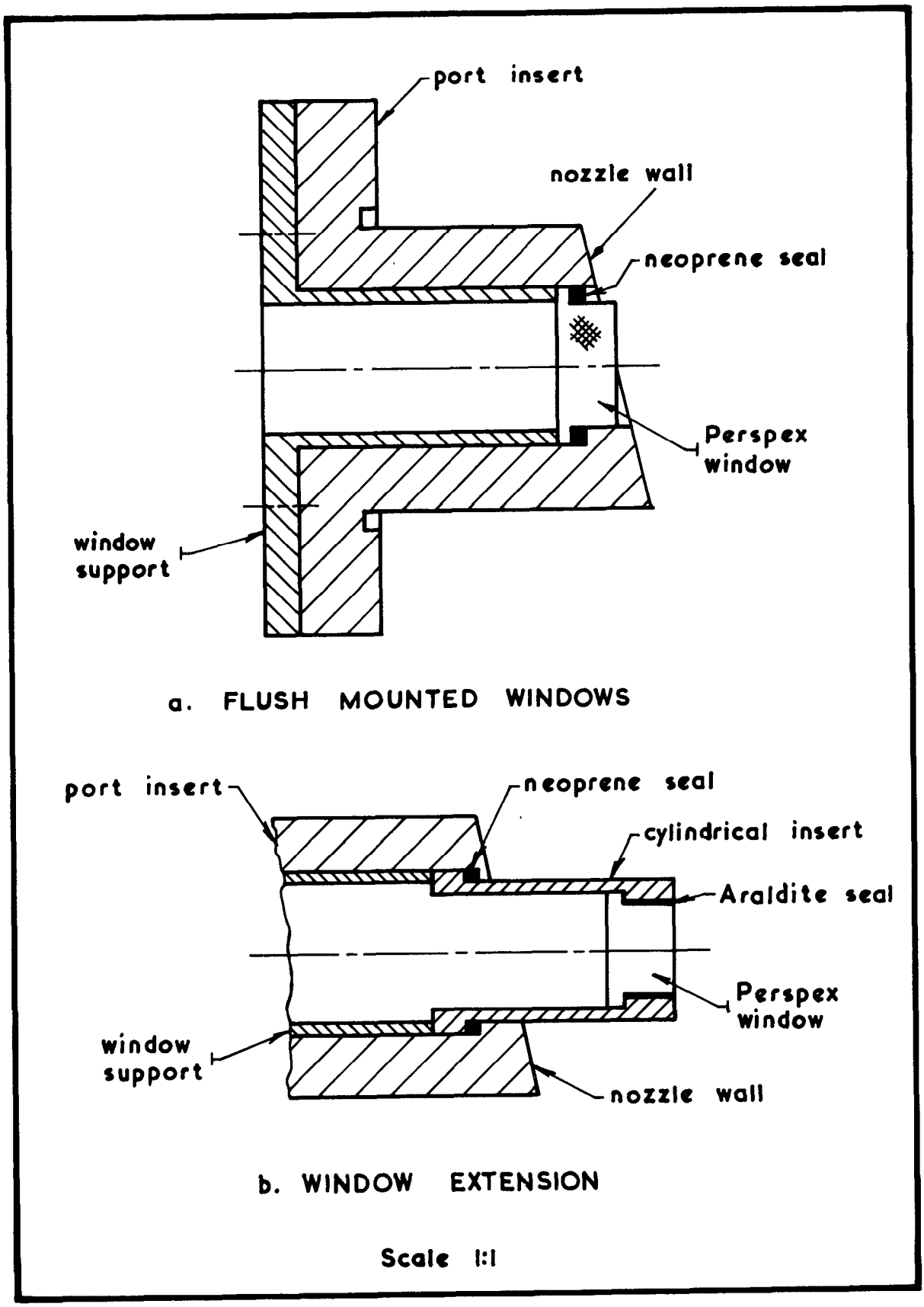


Figure 7 Conical nozzle window mountings

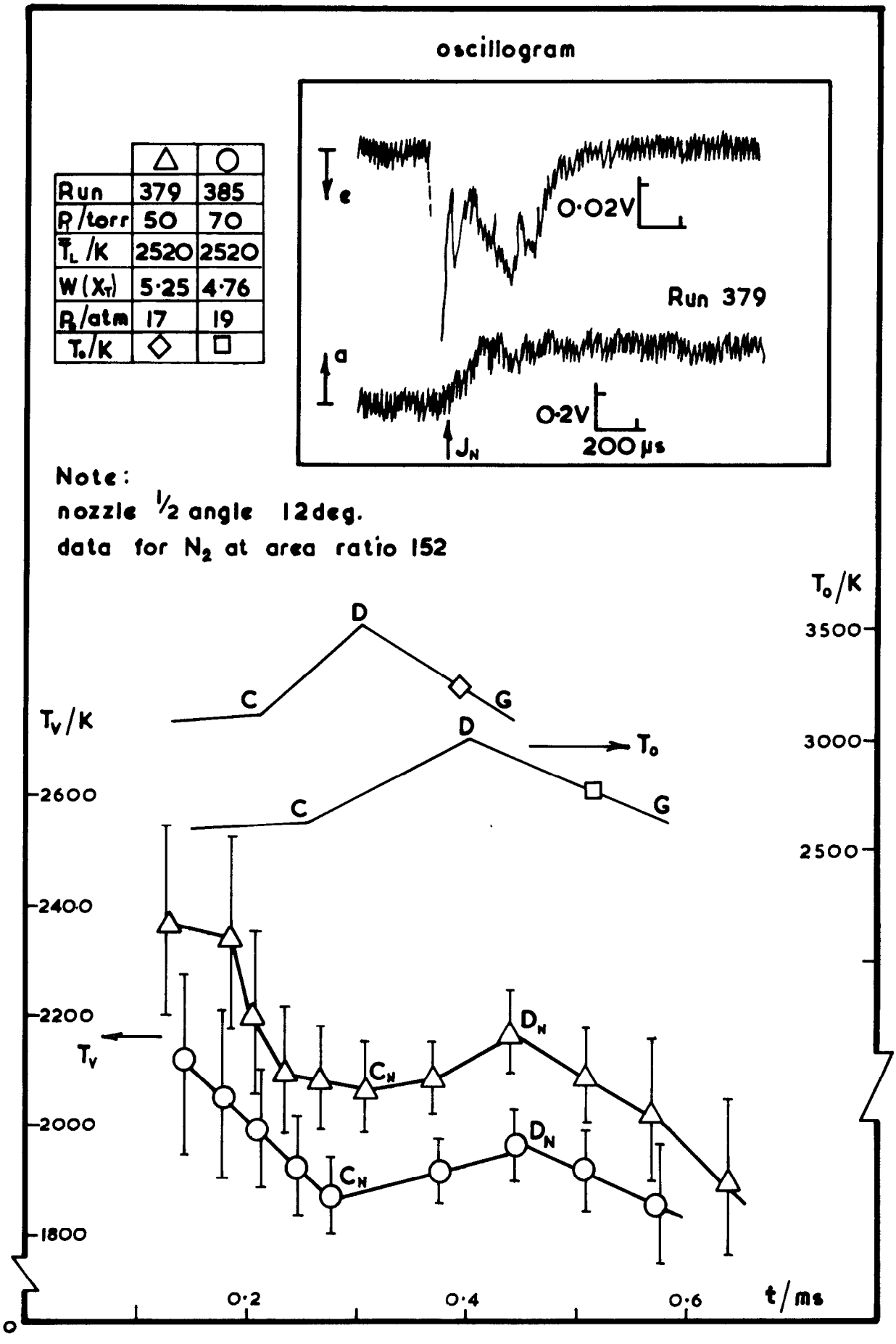


Figure 8 Vibrational temperature variation (conical nozzle)

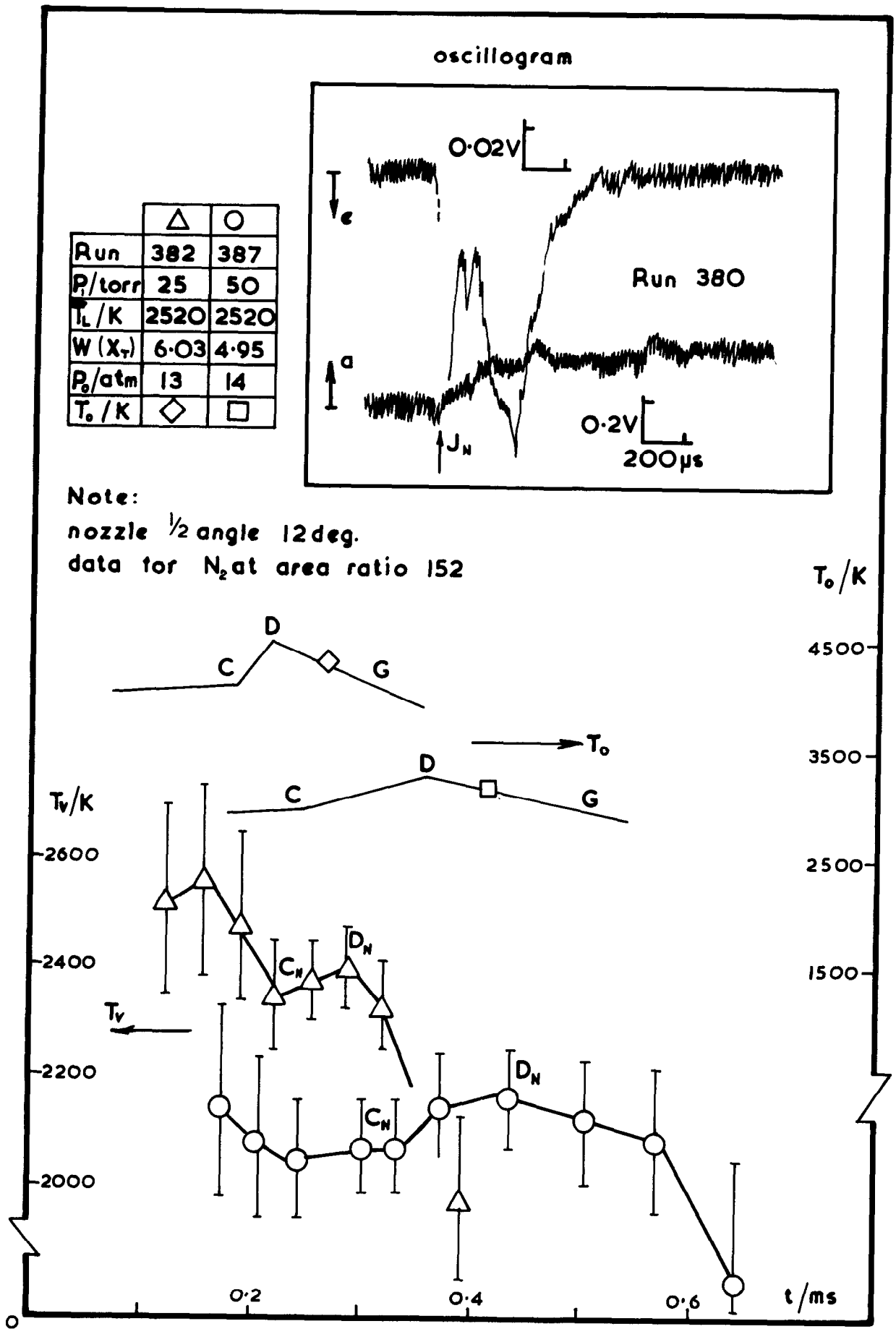


Figure 9 Vibrational temperature variation (conical nozzle)

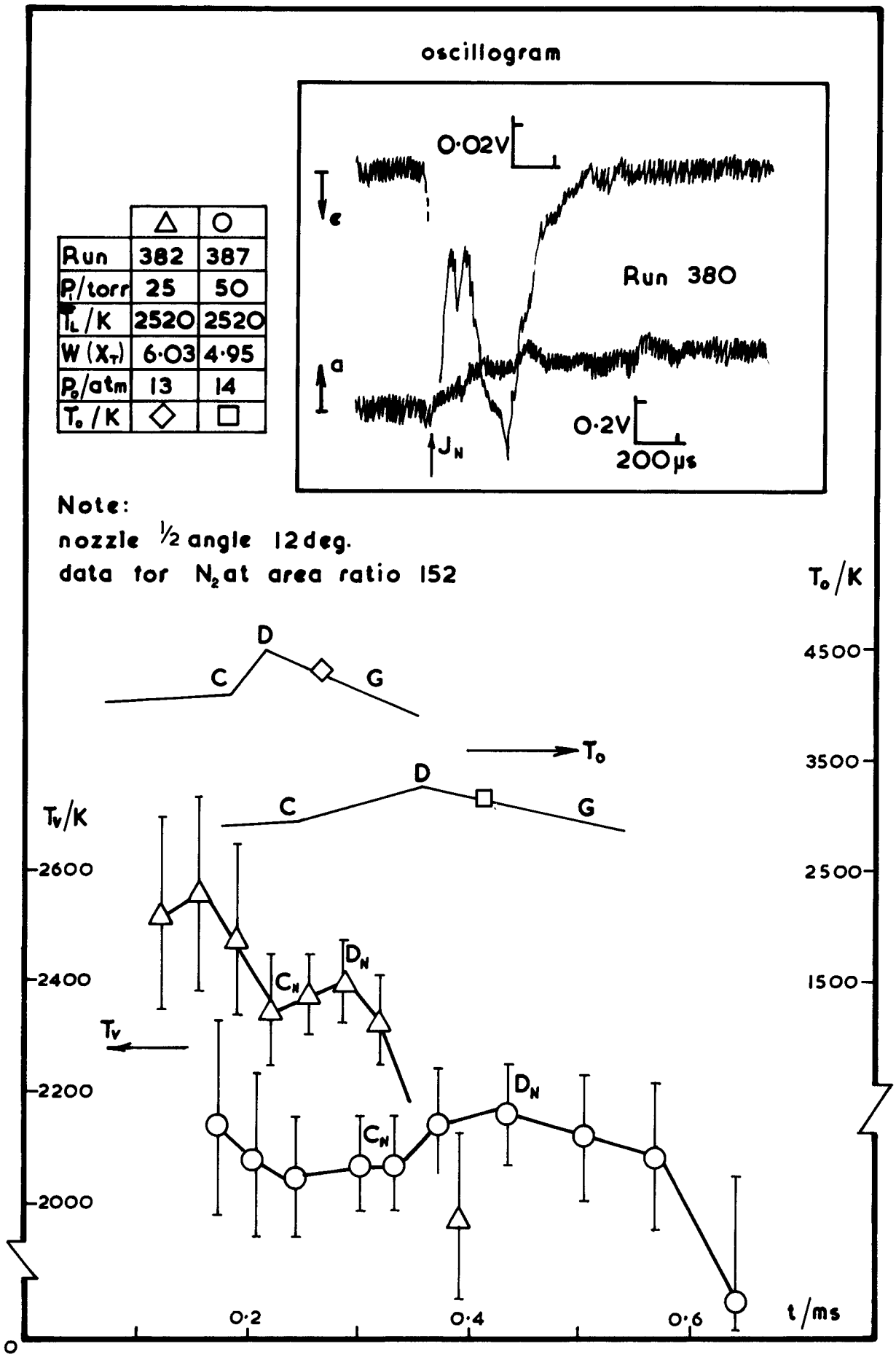


Figure 9 Vibrational temperature variation (conical nozzle)

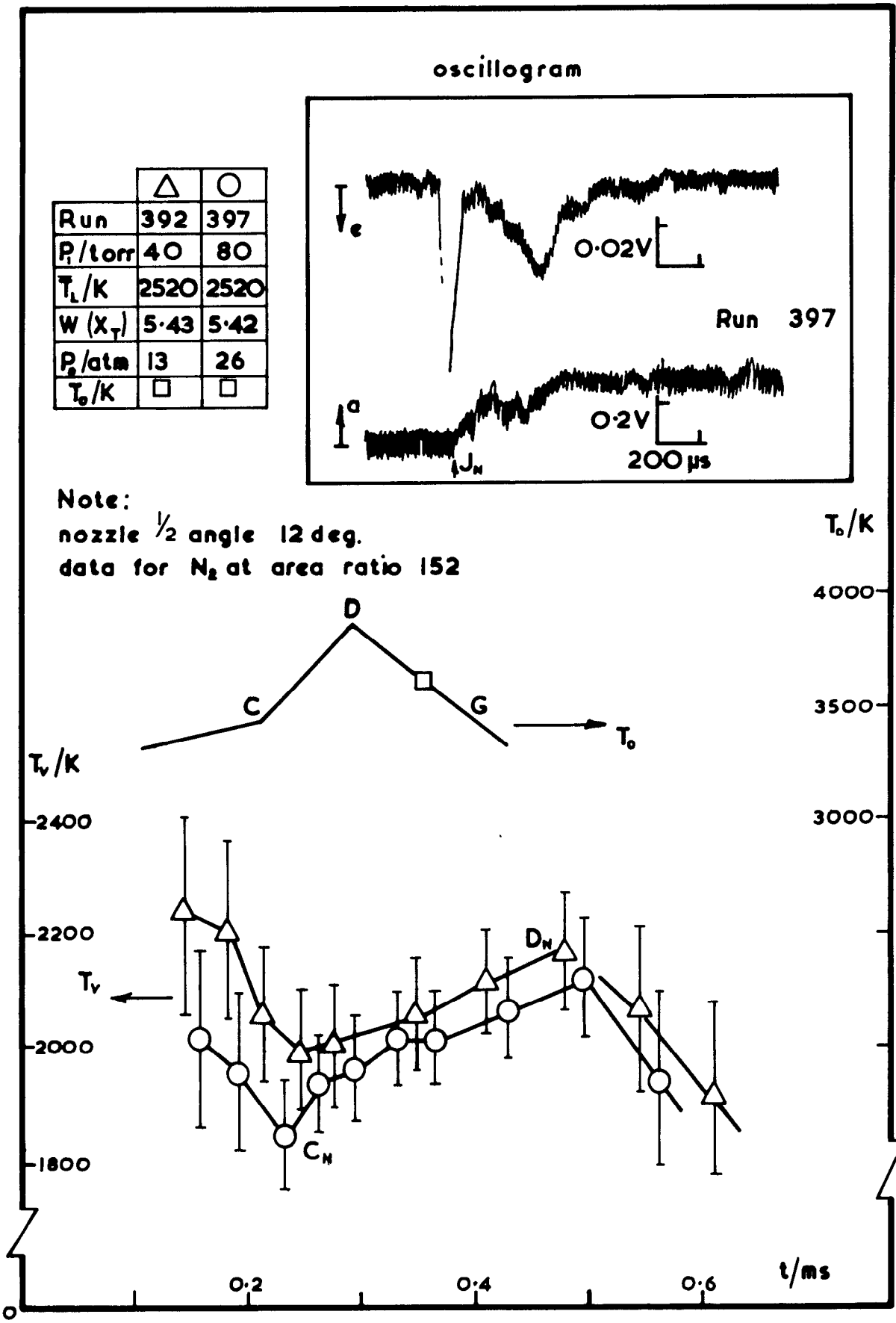


Figure 10 Vibrational temperature variation (conical nozzle) identical stagnation temperature

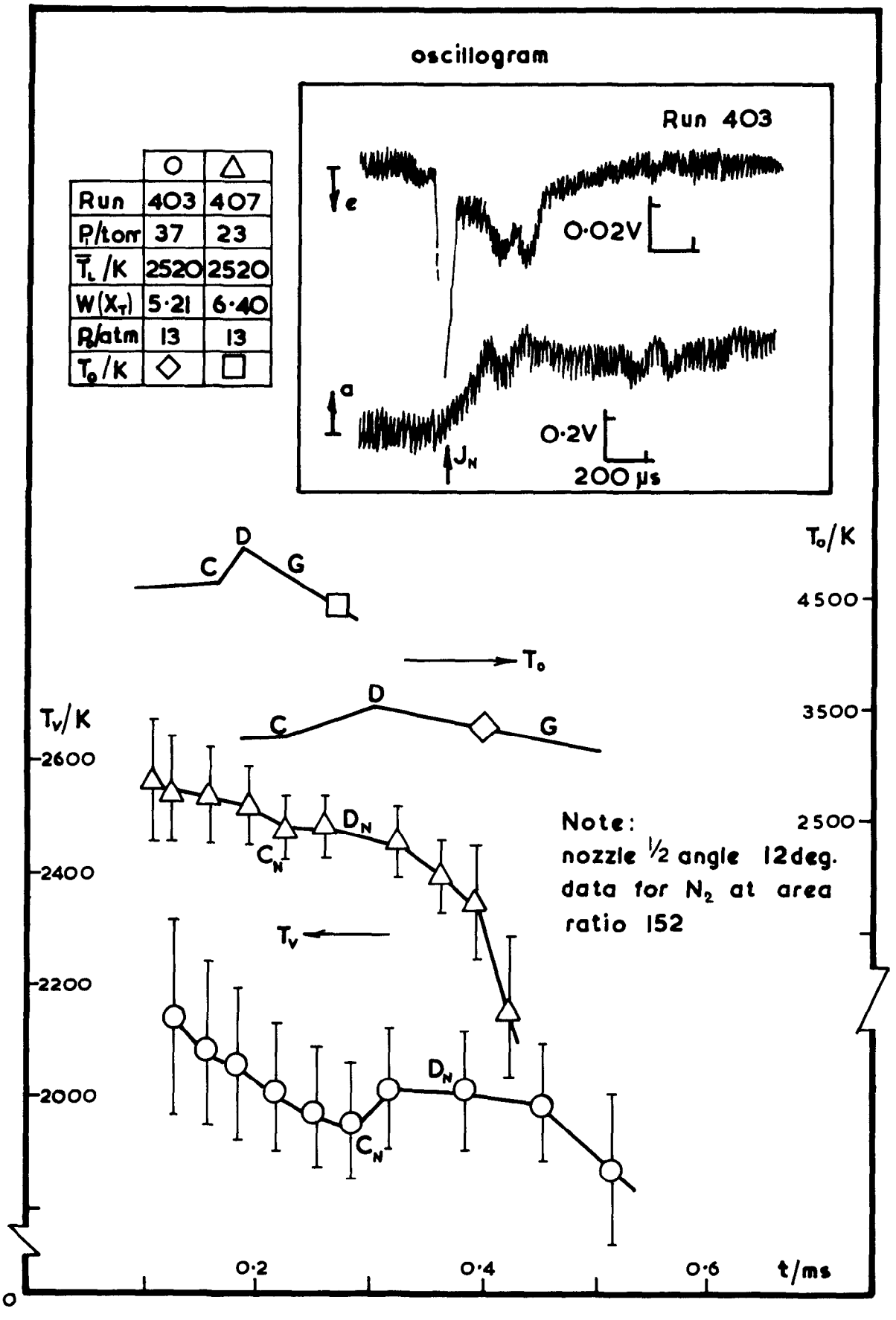


Figure 11 Vibrational temperature variation (conical nozzle) identical stagnation pressure

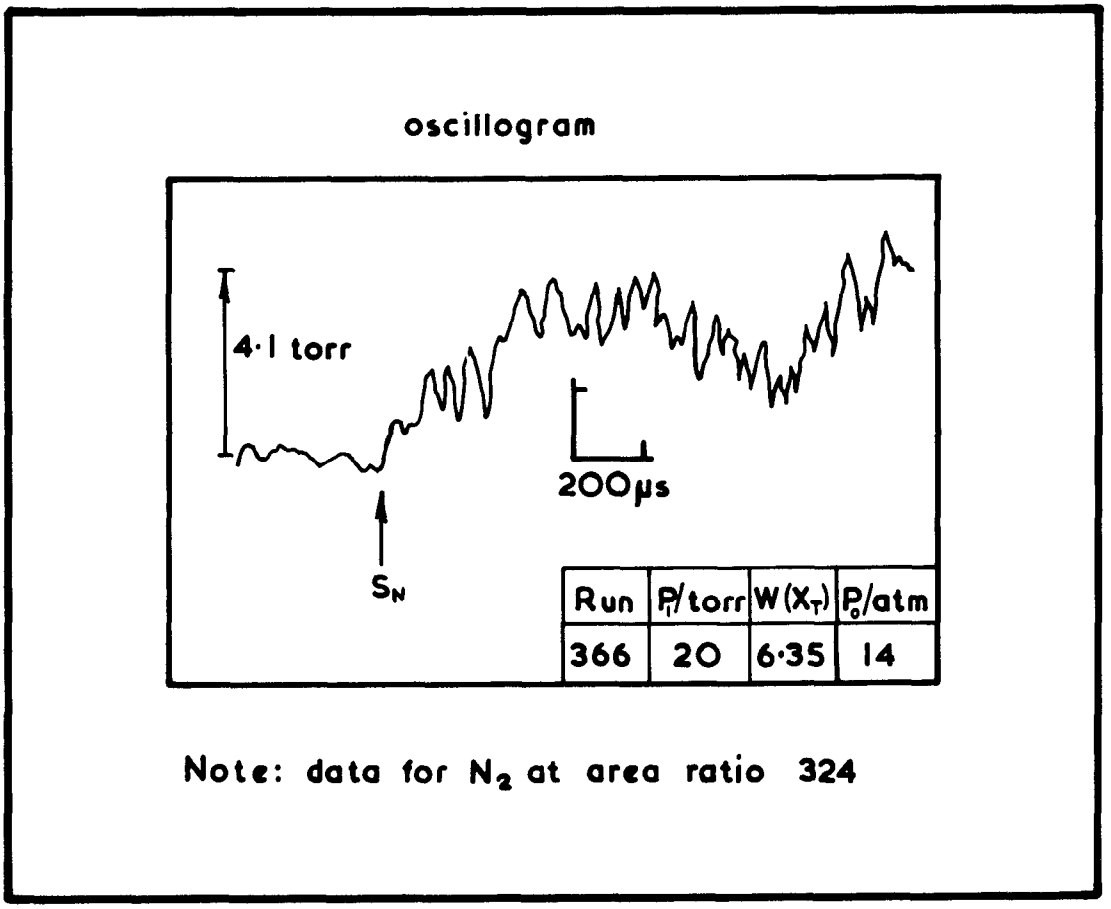


Figure 12 Static pressure variation at station B in the conical nozzle

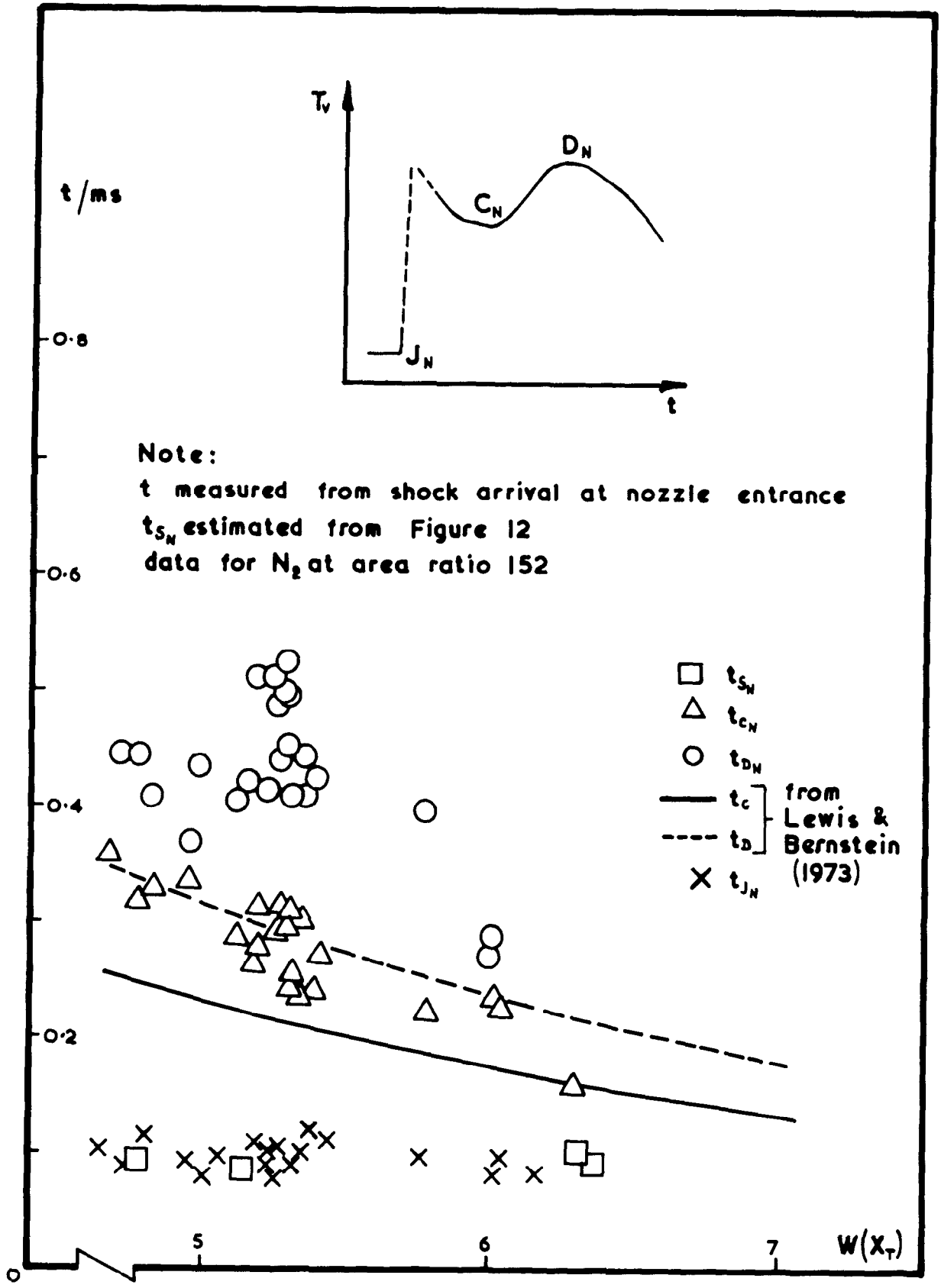


Figure 13 Hot flow duration at station AA' (conical nozzle)

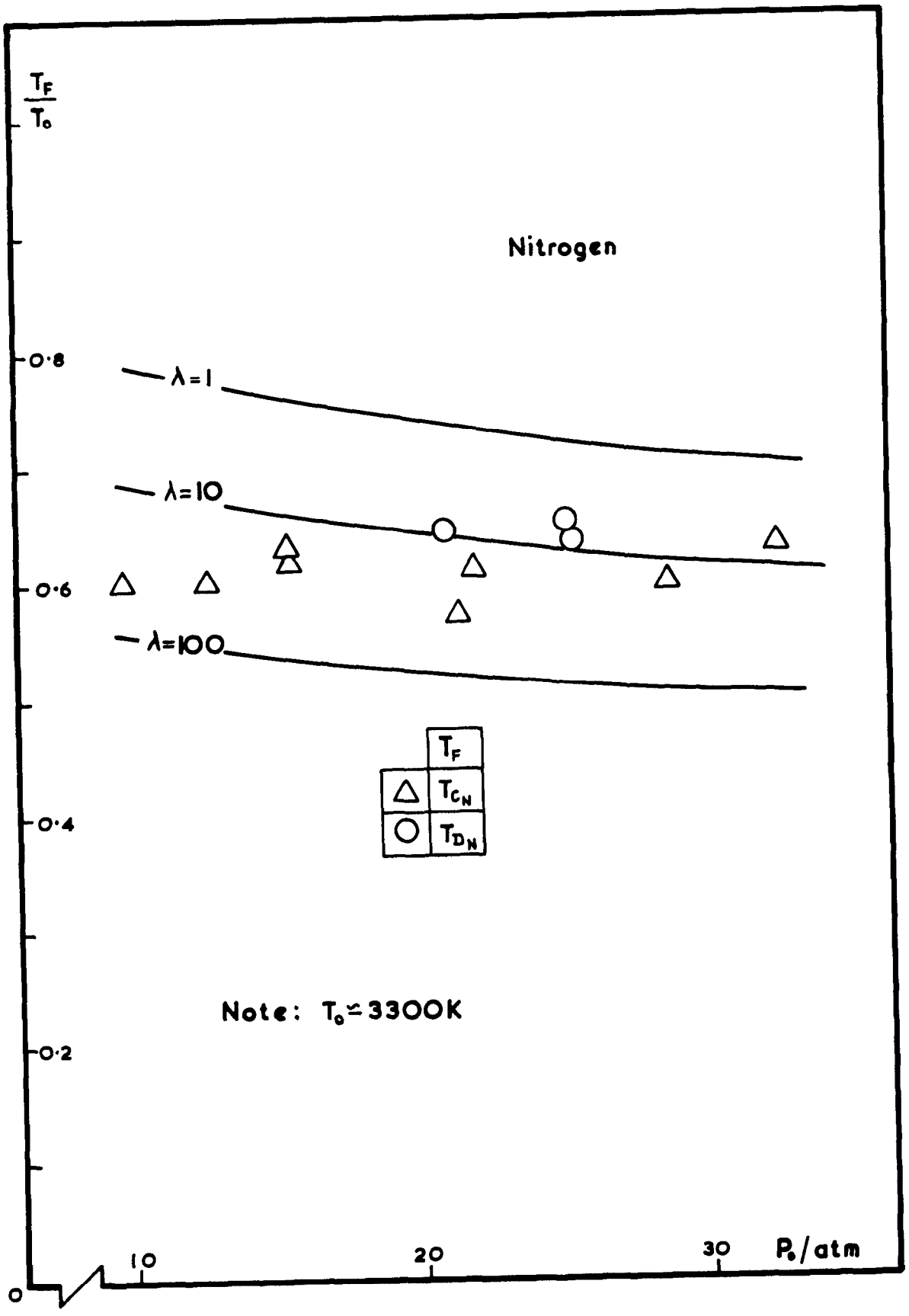


Figure 14 Calculated and measured frozen vibrational temperatures

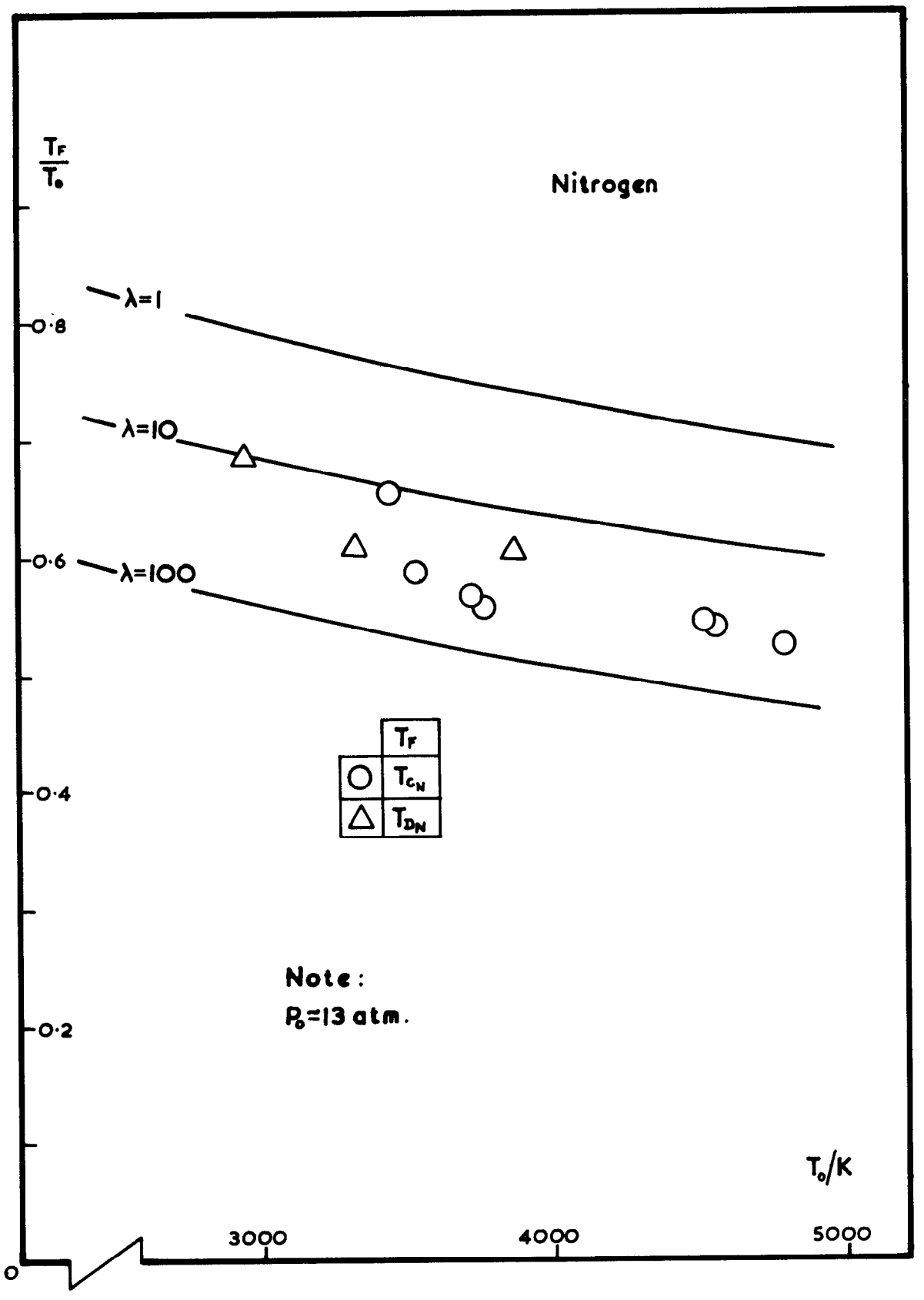


Figure 15 Calculated and measured frozen vibrational temperatures

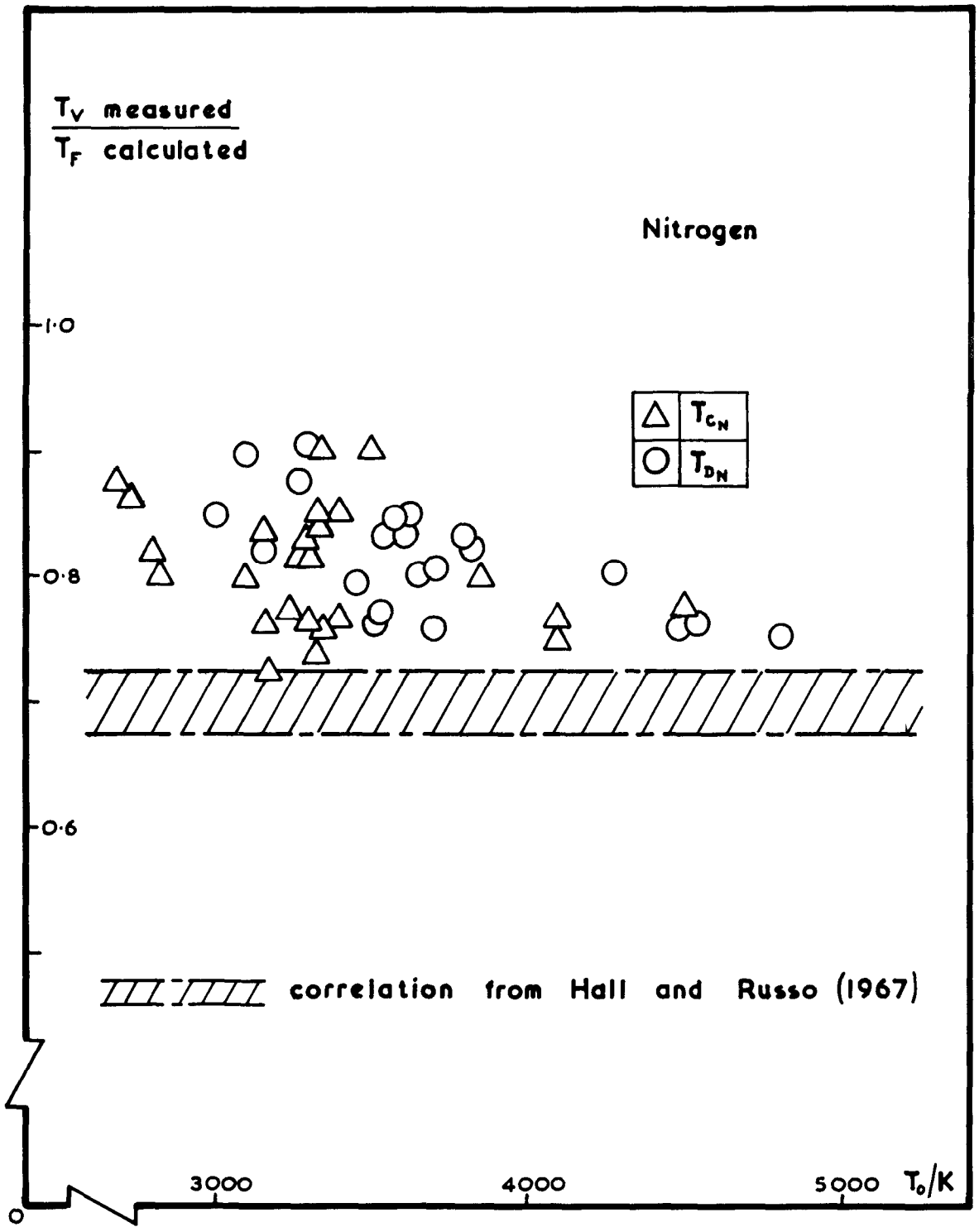


Figure 16 Correlation of frozen vibrational temperatures in the conical nozzle

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