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Oscillatory flows in ducts: a report on Euromech 73

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1. Introduction

Euromech Colloquium number 73, on 'Oscillatory flows in ducts', was held in Aix-en-Provence (France) from 13 to 15 April 1976. There were 56 participants from Britain, Denmark, France, Germany, Holland, Ireland, Japan, Norway, Poland, Spain, Sweden, Switzerland and the United States, and the author was the chairman of the meeting organization.

In 1971, Euromech 23, on 'Finite amplitude and diffusive effects in acoustics', was held. Progressing waves in an unbounded medium were excluded from the topics at the meeting, so that the bulk of the papers were concerned with flows in ducts. Since the topics considered at Euromech 73 included finite-amplitude and diffusive effects, the fields covered by the two colloquia overlap. In this way, several papers presented at the second colloquium showed the progress made in this research area since 1971.

Consideration of oscillatory or pulsed flows (compressible or incompressible) in ducts and cavities was included. The duct cross-section could be variable in space and/or in time. The flow of non-Newtonian fluids was outside the scope of the meeting. References quoted in this report include not only the lectures given at the colloquium but also sources of further details about the work presented at the meeting. The programme included three sessions: acoustics, viscous effects, and compressibility and thermal effects.

The aim of this report is to show the importance of the research at present being done on the subject and the great variety of interesting problems encountered in oscillatory flows. The author has not attempted to make a synthesis of the papers. He has rather tried, for each contribution, to indicate the most essential points that arose from the presentation itself and from the discussion that followed. He is very much indebted to the participants for their comments and criticisms when the manuscript was being prepared.

2. Acoustics

Of the twelve papers presented in this session, seven dealt with nonlinear problems. These papers led to a very intense discussion about what is really meant by nonlinearity.

Beginning with the observation that sound attenuation in pipes is strongly increased if the flow is turbulent, Ronneberger* has studied the interaction between sound and turbulence. On defining a parameter which is essentially the ratio of the thickness of the acoustical boundary layer to the thickness of the viscous sublayer, he has found that beyond a critical value of 5 interaction will occur. The trends of the experimental curve for the wall shear stress impedance can best be explained with a rather rough model of turbulence. That is, the transition from molecular viscosity in the viscous sublayer to the effective shear modulus in the turbulent region of the boundary layer can be modelled by a rigid plate parallel to the wall, from which the viscous shear is reflected.

Even as Bergh & Tijdeman (1965) had extended the linear viscous theory of Iberall to complex transmission lines, Tyvand* has further extended it to find the frequency distortion in such lines. He has expanded the flow variables in Fourier series in order to compute the second harmonic generated by a pure sinusoidal excitation and has thus found it to be proportional to the square of the excitation amplitude. Although the measured variation of the second-harmonic pressure oscillation as a function of excitation frequency followed the trend given by the theory, the experimental value of the amplitude is occasionally larger by a factor of 20 at harmonic and subharmonic frequencies. Tyvand attributed these discrepancies to local dissipation of oscillatory energy at the sharp edges and discontinuities present in the configuration tested.

Peube, Tartarin & Peube* have studied the nonlinear acoustics in a tube excited by a piston at one end and open at the other end. They expanded the solution in terms of the acoustical Mach number and took into account boundary-layer effects. The experimental values of the mean pressure are in good agreement with the theoretical ones, except near the tube mouth when the amplitude is large. This disagreement was explained by the observation that the flow pattern in this region is no longer one-dimensional and is governed by a frequency parameter defined as $a(n/\nu)^{\frac{1}{2}}$ (a = piston amplitude, n = frequency and ν = kinematic viscosity). When this parameter approached the value 6, during half of the period flow separation was observed within the tube at a distance of about half a diameter from the mouth and jet flow out of the tube occurred. During the other half of the period a sink-type flow was observed, without separation (see also Disselhorst* and Jimenez*). When the frequency parameter was equal to or higher than 26, a turbulent wake appeared at the mouth whereas the flow inside the tube remained laminar.

Beguier & Russel* have investigated the pulsations in static pressure and axial velocity generated by a rotator placed downstream of a test section of a cylindrical pipe with a smooth converging mouth. The pulsating movement was superimposed on a mean motion and the authors initially assumed that the fluid is incompressible and that the velocity pulsations are in phase over the entire length of the tube. By integrating Euler's equation along the axis, they calculated the static-pressure pulsations from the velocity pulsations that follow from this model. The experimental results showed that the model is too crude, so that the reflexion of the pressure waves which modulate the mean flow at the mouth needs to be taken into account. Since these waves travel with the speed of sound, their propagation and reflexion introduce a phase shift between the velocity pulsations in two different sections. In this way, the compressibility of the gas was taken into account. However, the relation between static-pressure and axial-velocity pulsations of the inertial movement continued to obey the *incompressible* Euler equation through an empirical reflexion coefficient and a complex 'inertial downstream length', which gives the influence of inertial terms. With this new model the authors obtained theoretical values which are in good agreement with the experimental ones.

Mortell* has considered the evolution with time of an input signal in a tube of finite length filled with gas. Under closed end conditions, the motion is periodic in time in the linear theory, whereas the signal will evolve with time in the nonlinear case, as shown by Lax. Mortell has studied the slow changes in the Riemann invariants due to nonlinearity. Using two time scales, he showed that the original problem, in which waves move in opposite directions and interact with each other, reduces to a unidirectional problem in a semi-infinite tube, for which solutions are known. Mortell indicated that the same approach can be used for the propagation of long waves in shallow water tanks of finite length.

Chester* first recalled the important points of the paper he published in 1963 on resonant oscillations in *closed* tubes. In this paper he had shown that, at resonance, the linear solution breaks down because of the linear boundary condition at the piston and not because of a failure of the wave equation. By applying the proper non-linear condition, he had shown that the amplitude of the oscillation remains finite even in the absence of dissipative mechanisms. He had also shown that shocks appear in a certain frequency band around the resonant frequency. These theoretical results have been remarkably confirmed by experiments. For an *open* pipe, however, the situation is complicated by the boundary condition at the open end. If the same analysis as for a closed pipe is carried through, the usual assumption of constant pressure at the open end does not lead to satisfactory results. Discontinuities of rarefaction waves appear which can be made to vanish only with a substantial dissipative mechanism. Several mechanisms have been postulated by various authors but none of them appeared to be entirely satisfactory to Chester. For the open pipe, he wants to solve a linear problem with a nonlinear boundary condition, or a problem where no substantial distortion occurs from *intrinsic* nonlinearity. In most known experiments, however, this distortion is present and comparison with Chester's theory is not possible.

The paper of Keller* (presented by Rott) dealt with subharmonic nonlinear resonances in closed tubes. The author investigated what happens when an overtone of the displacement function of the piston is in resonance with the gas column in the tube. He showed that, when an oscillation is driven at $1/n$ of the fundamental frequency, Chester's theory has to be extended to nth order. He found that shocks occur only in a correction of order $M^{\frac{1}{2}n}$ to the acoustic solution of order M (where M is the acoustic Mach number). The width $\Delta\omega$ of the resonant region was shown to become smaller for larger values of n ($\Delta\omega/\omega \sim M^{\frac{1}{2}n}$). Moreover, the viscous effects have a stronger damping influence with increasing n. This is why it should be difficult to observe shocks in the subharmonic regimes experimentally. Of particular interest is the case $n = 2$, where a correction of order M indicates a genuine breakdown of linear acoustic theory.

Disselhorst* has studied the finite-amplitude oscillations in an open resonance tube. He found three regimes of operation. In the first regime, at small piston amplitude δ, the wave equation and the boundary condition are linear. An effective impedance can be defined and is related to acoustical and boundary-layer dissipative effects. The experiments showed, however, that there is more damping present than can be accounted for by these effects, and this is probably due to additional viscous losses outside the tube. In the second regime, for larger δ, the wave equation is still linear whereas the boundary condition at the open end is nonlinear. As was previously done by van Wijngaarden (1968), Disselhorst divided the flow into a jet flow at constant pressure during outflow and a sink flow during inflow. He observed periodic vortex building, especially if the edge of the tube exit was sharp rather than smooth. With a sharp edge, a vortex formed during inflow and was blown out during outflow. This caused a strong dissipation effect. Also, it was found that with a sharp edge the oscillations passed into the second regime at a considerably lower piston amplitude. If the radius of curvature of the edge was so large that boundary-layer separation occurred only at outflow, the piston pressure amplitude $\hat{p}$ was proportional to $\delta^{\frac{1}{2}}$, theoretically as well as experimentally. In the third regime, not only is the boundary condition nonlinear but so is the wave equation. However, the experimental arrangement did not appear to be suitable to reach this regime. (At $\omega = 290\,\mathrm{s}^{-1}$, $\delta_{\max} = 3{\cdot}95$ mm and $\hat{p} = 15400\,\mathrm{N/m^2}$).

Jimenez* compared his previously published theoretical results on nonlinear resonance in open pipes with experiments run at Caltech by Sturtevant (1974). In these experiments, the piston amplitude was very large, so that nonlinear effects were also quite large. This was because the wave form was not the same near the piston as it was near the open end. Shocks formed from the piston to the end. At high amplitudes thin shocks also seemed to appear near the piston. In his theory, Jimenez used the model of acoustic impedance at the open end of the pipe and empirically chose the impedance parameter to give the best fit with the experiments. However, he pointed out that the model of jet-like flow at the exit and sink-like flow at the inlet, first proposed by van Wijngaarden (1968; see also Disselhorst*), gives better agreement with experiments and also has the advantage of not requiring an additional parameter to be adjusted. Jimenez indicated that van Wijngaarden's model is good when the flow may be regarded as quasi-steady near the open end, in which case the Strouhal number D/UT (where D represents the tube diameter, U the gas velocity at the open end and T the period of the oscillations) is small.

In the discussion that followed, Chester criticized the comparison of experiments in which intrinsic nonlinearity of the wave is present (experiments in which a distortion of the wave occurs as it moves along the tube) with a theory which is *not* intrinsically nonlinear. Chester suggested that when distortion of the wave is present the approach of Mortell* should be used.

Valk* presented an experimental investigation on the acoustic energy radiated by a fluctuating flame. This problem is related to the so-called 'combustion-driven oscillations' which can spontaneously occur when a burner is located within a combustion chamber. In the apparatus used by Valk, oscillations did not occur spontaneously but were driven by pistons: one of them drove the mixture supply of the burner and the other produced pressure oscillations in the combustion chamber. By writing down an acoustic energy balance, he was able to measure indirectly the acoustic energy released by the flame. The experimental results verify the Rayleigh criterion, which states that only the part of the fluctuating heat release which is in phase with the pressure contributes to the addition of acoustic energy.

Möhring* has studied theoretically Kelvin–Helmoltz instabilities for compressible flow in soft-walled ducts. In such ducts, an inward local displacement of the wall produces a decrease in pressure at that point. This lower pressure tends to increase the inward displacement whereas the wall impedance produces a restoring force in the opposite direction. Depending on the relative magnitude of these two forces, instabilities will or will not occur. Möhring considered a small perturbation of a uniform flow in a duct which led to a convected wave equation for the pressure. He showed the influence of the wall susceptibility, the wave-number and the Mach number on the occurrence of instabilities.

Ribreau* has investigated wave propagation in an annular duct containing an incompressible medium which makes periodic oscillations. The inner duct was a soft-walled duct whereas the outer duct was a hard-walled duct. The inner duct was subjected to an over-pressure so that there was an initial stress in the soft wall. A sinusoidal pressure signal was sent into the annular duct by a pump. There are two modes of wave propagation: the longitudinal one (Lamb) and the transverse one (Young). Ribreau temporarily restricted himself to the second. He experimentally determined the relation between the pressure p and area A and used this experimental law to calculate the wave speed c from

$$c = (A\rho^{-1} dp/dA)^{\frac{1}{2}},$$

where ρ represents the density of the incompressible medium. Experimental values of c are in good agreement with those obtained by this simple theory (except when the initial stress tends to zero) provided that viscous effects are taken into account.

3. Viscous effects

A large number of the papers presented in this session dealt with incompressible media and had an obvious relation to haemodynamics. Studies on laminar, transitional, turbulent and separated flows were presented.

Dantan, de Jouvenal & Oddou* were interested in the onset of instability of pulsed flows in cylindrical ducts, with physiological flow problems in mind. The dynamical properties of pulsed flows are generally determined by three parameters: the Reynolds number based on the mean flow velocity ($\overline{Re} = \overline{w}2R/\nu$), the amplitude parameter ($\lambda = \tilde{w}/\overline{w}$) and a frequency parameter [$\alpha = R(\omega/\nu)^{\frac{1}{2}}$]. In physiological flows, the Reynolds number based on the peak velocity also plays a role ($\check{Re} = \check{w}2R/\nu$). The linear theory of small perturbations (with the quasi-steady flow hypothesis) permits an analysis of the stability of velocity profiles with two types of criteria. The first, which applies when α is large (small viscous effects), is that instability should occur when the velocity reversal and generation of vorticity fluctuations occur simultaneously. The second criterion for the onset of instability occurring when viscous effects play a role, is that $\overline{Re}$ should be smaller than an empirical constant divided by the maximum value (in time and space) of the velocity gradient. The authors applied these criteria to various experiments run *in vitro* and *in vivo* and showed that, in general, the agreement is fairly good, taking into account the difficulty of the problem.

Inspired by previous studies on oscillating pipe flow (Clarion & Pélissier 1975; Merkli & Thomann 1975), in which eddies of large amplitude were observed before turbulence appeared, Tromans* further investigated this phenomenon with dye streaks in water. The frequency parameter (ratio of tube radius to Stokes-layer thickness δ) was quite large in his experiments. The Reynolds number based on δ was found to be about 130 for the onset of instability and 500 for the onset of turbulence. The wavenumbers of the disturbances and the distance of the eddy from the tube walls have been measured from photographs. The observed wavenumbers showed fair agreement with the quasi-steady stability analysis of von Kerczek & Davis (1974). In the discussion, Rott pointed out that in previous experimental investigations the instabilities have been shown to occupy only a fraction of the whole cycle, so that the phenomenon is beyond the stability method generally used. Rott suggested that the correct approach is that made by Clarion & Pélissier, in which the disturbance is observed in a system moving with the flow velocity.

Péronneau, Sandman & Xhaard* have made an experimental study of flow stability under pulsatile conditions. They used an ultrasonic pulsed flowmeter based on the Doppler effect which they had described previously (1974). The flow was characterized by a peak Reynolds number and a disturbance index. Following McDonald & Womersley, they defined the peak Reynolds number Re_p as $(R^2/2\nu)\,(\partial v/\partial r)_{\max}$, where $(\partial v/\partial r)_{\max}$ represents the maximal radial velocity gradient obtained at peak flow. For a sample volume and for a given short period of time, the Doppler effect gives a signal for which the spectrum of zero-crossing frequencies is related to the fluid velocity. Characterizing the spectrum by its mean value $\bar{v}$ and its standard deviation ϵ, the disturbance index is defined as the ratio $\epsilon/\bar{v}$. Péronneau *et al.* measured this index as a function of Re_p for a straight pipe and an obstructed pipe. The influence of an obstruction on the disturbance index was shown to be quite large throughout the range of Re_p considered (500–3000).

Jonsson* presented velocity measurements in a rough turbulent boundary layer using a large oscillating water tunnel (10 m long horizontal test section with height × width = 30 × 40 cm). On the basis of the velocity, measured as a function of time and height over the wall, the shear stress was calculated using the equation of motion. Subsequently, a semi-empirical expression for the friction factor, which is a function of horizontal particle amplitude over bed roughness, was found. This empirical expression is very close to the theoretical result of Kajiura. In order to compare his measurements with other measurements made with an oscillating wall, Jonsson introduced transformed values of the velocity and phase angle (called 'defect' values). He showed that certain universal velocity and phase relationships exist in oscillatory rough turbulent boundary layers.

A logarithmic velocity overlap layer was found and this resulted in a new relationship between the friction factor and the ratio of the boundary-layer thickness to the roughness. When the ratio of particle amplitude to roughness is larger than 30, a method was proposed for the prediction of the phase shift between the maximum velocity in the free stream and the maximum shear stress at the wall.

Houdeville, Desopper & Cousteix* have made an experimental analysis of turbulent characteristics of an oscillatory boundary layer. They produced pulsating flow (mean velocity 87 m/s, amplitude and frequency of velocity fluctuation 25 m/s and 46 Hz) in a wind tunnel (cross-section 100×110 mm) by means of a rotating vane. The velocity measurements were made with hot wires. A synchronization system connected to the vane permitted measurement of an ensemble average of the velocity. This quantity is composed of an average velocity u and a fluctuation velocity u' (turbulence). The average velocity profiles showed a small positive phase shift which exhibited a maximum of 11° at $y/\delta = 0{\cdot}2$ (δ = boundary-layer thickness). Although its velocity changed sign near the wall, the boundary layer was not thick enough to obtain detailed results in this region. The turbulence intensity profile was not in phase with the mean velocity except in the external flow and near the wall. In the latter region it seemed that the structure of the turbulence was not sensibly affected by the unsteadiness of the flow. However, more experiments are required to verify this. Finally, Houdeville *et al.* applied the transport equations to the calculation of the boundary layer and got encouraging results.

In the discussion, Woods reported that turbulence measurements made in a reciprocating engine showed large-scale oscillations and then asked if an analogous effect had been detected by Houdeville *et al.* This requires a measurement of the frequency spectrum and they were sceptical about the value of such a test in an oscillating flow.

Ly, Bellet & Bousquet* have investigated analytically and experimentally the transient, viscous, flow phenomena that occur in a cylindrical duct when a longitudinal pressure gradient is suddenly applied. In the analytical study they used the Laplace transform and calculated the velocity profiles for various model applied pressure gradients (step, sinusoidal wave train, and so on). The velocity was measured by a laser with the incident laser frequency modulated to distinguish between positive and negative velocities. To compare theoretical results with experimental results the authors first measured the pressure gradient. By an adequate combination of the various models they matched the theoretical pressure gradient to the measured one. The comparison of experiments and theory gave good results. Ly *et al.* are now planning to use their method for studying the flow of non-Newtonian fluids.

Doffin, Chagneau & Borzeix* have investigated oscillating, viscous, incompressible flow in a duct of varying cross-section. The duct cross-section considered was periodic with a wavelength λ, which was supposed to be greater than the average tube radius r_0. They expanded the stream function ψ in powers of $\delta = r_0/\lambda$ and found successive approximations for ψ. The zeroth-order solution was found to be entirely unsteady and corresponds to Stokes motion in a cylindrical tube. The first-order solution contains a steady and an unsteady part. The second-order solution is entirely unsteady. The calculations were carried out for several values of the Reynolds number ($Re = u_0 r_0/\nu$) and of the frequency parameter [$R_0 = r_0 (\omega/\nu)^{\frac{1}{2}}$]. It was found that the influence of the Reynolds number on the flow pattern is small and that the steady velocities are very small at small Reynolds number. The method applies up to a Reynolds number of about 30. Experimental investigations were planned to verify these results.

Lebouché & Martin* reported experiments made on the flow in a duct which undergoes a sudden enlargement on both sides (two-dimensional step). Specifically, they measured the wall shear stress with electrochemical probes. The flow downstream of the step consisted of two regions: a three-dimensional recirculation zone (in the step corner) in which the velocity near the wall was in the same direction as the mainstream and a two-dimensional recirculation zone in which the velocity near the wall was in the opposite direction. In the first series of experiments, although the main flow velocity was steady they showed that the flow in these zones is unsteady. The mean position of the reattachment point was about seven times the step height h, but fluctuations of $\pm 1{\cdot}3h$ around this mean value were observed. The influence of main-flow pulsations on the flow downstream of the step was then studied. The amplitude of the pulsation was up to 30 % of the mean velocity u_0 and the frequency F ranged from 3 to 23 Hz. The various flow configurations observed were shown to depend on a reduced frequency $F^* = Fh/u_0$. For high pulsation rates, there existed a critical frequency $F_c^* \simeq 0{\cdot}07$ such that (a) if $F^* < F_c^*$, the recirculation vortex was shed, (b) if $F^* \simeq F_c^*$, the vortex was very unstable and (c) if $F^* > F_c^*$, the vortex was stable but was smaller than for steady flow. With air as the flowing medium, heat-transfer measurements downstream of the step indicated that the Nusselt number was substantially modified by the flow pulsations.

Mainardi, Barriol & Panday* have made a study of the modification of the instantaneous discharge coefficient of an orifice plate placed in a turbulent pulsating flow using a one-dimensional theoretical model which takes into account the acoustical characteristics of the ducts upstream and downstream of the orifice plate. This problem is of importance in measuring the flow rate of a pulsed flow by the orifice technique. Among other things, they found that, for the frequencies (up to 50 Hz) and for the modulation ratios (5–15 %) used in their investigation, the total-head loss coefficient was not affected by the pulsations, whereas the discharge coefficient was modified by 1·5 % or 4 % when the modulation ratio was 5 % or 15 %.

Teipel* has investigated the effect of a uniform distribution of dust particles on the pulsating viscous flow in a circular pipe. Assuming that the force between the phases is given by Stokes' law, he found the exact solutions for the fluid velocity profiles and particle velocity profiles in terms of Bessel functions with complex arguments. The important parameters are a frequency parameter $\omega R^2/\nu$, a relaxation parameter, the ratio of the mass density of the particles to the fluid density, the mass concentration of particles and the pressure gradient. Teipel showed numerous calculated profiles for various values of these parameters. He also showed the asymptotic form of the solution for small and large values of the frequency parameter. On the basis of his computations, he indicated the experimental difficulty of measuring the fluid velocity in unsteady flow when the fluid contains dust particles. In particular, this difficulty could arise with laser anemometry. In the discussion that followed, many participants raised a question about the applicability of Stokes's law. The possibility of transverse motion, rotational motion, hydrodynamic interaction and the Magnus effect in shear flow could perhaps modify the theoretical results obtained by Teipel. In any case, it was felt that the problem is of great importance and warrants further investigation.

Durin* has studied experimentally pulsed flow in a deformable long duct. The duct was rectangular in shape, three sides being rigid (Plexiglas) and one side elastic (rubber). A pulsated flow was superimposed by a pump on to a mean flow. The propagation and the reflexion of a deformation wave in the rubber produced a forced pseudo-standing wave in the duct, so that there existed a fundamental frequency and harmonics. Also, there were nodes and antinodes for the pressure amplitude. The experimental methods included measurements with pressure gauges, measurements with hot-film gauges and flow visualization. Durin was particularly interested in the flow development on a small obstacle placed on the (rigid) bottom of the duct. In a very spectacular movie, shown at the meeting, the flow over a small half-cylinder with axis perpendicular to the main flow direction was visualized by dye. For fixed values of the mean pressure and of the mass flow the occurrence and the position of vortices near the obstacle were found to depend on the pressure amplitude there. The appearance of vortices substantially modified the wall stresses downstream of the obstacle.

4. Compressibility and thermal effects

In this session, most of the contributions dealt with thermal phenomena which are caused by or produce gas motion (Hartmann–Sprenger tubes, Sondhauss tubes and Rijke tubes). Great progress has been made in this area since Euromech 23, particularly on the Sondhauss phenomenon.

Iwamoto* has studied the effects of cross-sectional variation in a Hartmann–Sprenger tube on the observed wall temperatures. He reported numerous experimental data which not only confirmed previously published results by other authors but also permitted some additional conclusions to be drawn. Iwamoto showed that the internal geometry of the tube (converging or diverging) strongly modifies the so-called 'instability intervals' of Hartmann. As the tapering of the tube increased, for example, thermal effects were intensified but the width of the instability intervals became narrower. The wall temperature distribution was found also to depend on the tapering.

Kawahashi & Suzuki* presented numerous results of theoretical and experimental investigations on Hartmann–Sprenger tubes. They showed that the insertion of a rod on the axis of a converging nozzle out of which flows a supersonic under-expanded jet increases the range of the inlet–ambient pressure ratio for which oscillations are observed. The thermal effects were also stronger with the rod. They also studied the influence of the tube material and showed that higher wall temperatures were recorded with stainless steel than with copper. In their theoretical work they attempted to calculate the equilibrium temperature of the tube wall and of the gas. The method used was a finite-difference scheme. Theoretical values for the wall temperature were in relatively good agreement with the experimental ones. The discrepancies were explained by the fact that Kawahashi & Suzuki neglected the heat evacuation by mass transfer at the contact surface. Near the closed end of the tube, the theoretical values of the gas temperature were found to be much higher than the end-wall temperature. Unfortunately no experimental results were available to verify this. Kawahashi & Suzuki then displayed the results of their investigation on the transient thermal phenomenon. Finally, they demonstrated that a secondary resonator may have a strong influence on the oscillatory frequency and on the thermal effects.

Rosen* has studied the feasibility of using a Hartmann–Sprenger tube for thermal ignition of hydrazine-based propellants. He indicated several advantages of this technique compared with catalytic ignitors. One of the requirements is to produce a heating rate of more than 300 °K in less than one second. Although higher heating rates have already been achieved by other investigators, the difficulty encountered here was that the device should operate in ambient vacuum conditions with the jet stagnation pressure in the range 10–200 Torr. This means that the jet power level and, consequently, the heating rate were considerably lower than for the case of atmospheric ambient pressure. Rosen sought to optimize various geometrical parameters. All his experiments were run with an under-expanded jet sonic nozzle and he found an optimal pressure ratio for this jet configuration. This pressure ratio depended on the ratio of the tube cross-sectional area to the nozzle cross-sectional area. In conclusion, he felt that this particular application of the Hartmann–Sprenger tube is feasible.

In recent years, Rott has carried out extensive investigations on thermally driven acoustic oscillations. These oscillations can occur spontaneously when the closed end of a tube (open at the other end) has a higher temperature than the open end (known as the Sondhauss effect, or Taconis oscillations in cryogenics). At the meeting, Rott & Zouzoulas* gave the latest results obtained on this subject. Recalling that the crucial fluid-dynamic parameter is the ratio of the tube radius to the Stokes boundary-layer thickness $\delta_s = (\nu/\omega)^{\frac{1}{2}}$, they investigated various possibilities of decreasing the critical value of the ratio α (of hot-end temperature to cold-end temperature) to obtain oscillations. They showed that this can be achieved by increasing the ratio of the tube diameter r_2 in the hot region to the tube diameter r_1 in the cold region. For N_2, increasing r_2/r_1 from 1 to 2 leads to a reduction in $\alpha_{\min}$ from 5 to 3·1. When the cold open end drives a liquid column, the critical temperature ratio is even lower. For hot air driving a water column, $\alpha_{\min}$ is only 1·5 and this was spectacularly demonstrated at the meeting with experimental apparatus.

Peube, Chasseriaux & Ashok* presented investigations on the other well-known thermoacoustic phenomenon, namely the Rijke phenomenon. The original configuration used by Rijke consisted of a heated grid mounted inside a vertical tube. In the experiments reported by Peube *et al.*, the tube was replaced by a resonator of a cylindrical shape. The bottom and the top of the cylinder were partially closed by two plates with circular orifices. With this configuration the oscillations did not occur spontaneously and were therefore excited by a loudspeaker. Measurements of the oscillation amplitude in the tube showed that the input oscillation was either amplified or attenuated, depending on the height e of the grid over the bottom of the resonator, on the one hand, and on the resonator height h, on the other. For large h, amplification was observed and increased when decreasing e. For small h, attenuation was always observed. Some of these experimental facts were confirmed by the linearized acoustic theory developed by Peube *et al.* for a duct of variable cross-section with heat addition.

Anderson *et al.** described experiments on the flow oscillations which occur spontaneously in a duct fed by a convergent nozzle followed by a sudden enlargement. The duct exhausted into a chamber in which the pressure could be varied. At very low chamber pressure, the flow in the duct was steady supersonic with oblique shock waves. Increasing the pressure made the flow separate from the duct wall and the separation point moved gradually upstream, from the plenum to the point of reattachment of the flow coming from the nozzle. Depending on the position of the separation point, three modes of oscillation were observed. In the first mode, the separation point lay within the plenum but not too close to the reattachment point; the oscillations were small and irregular. In the second mode, the separation point was close to the reattachment point; the oscillations were more regular and of low frequency, but there were no pressure oscillations in the dead-air region. In the third mode, the separation point and the reattachment point merged; the oscillations had a higher frequency and there was a pressure oscillation in the dead-air region. Generally speaking, the oscillation frequency was determined by the duct length. The oscillation mechanism appeared to be determined by boundary-layer effects.

Bushell & Woods* reported experiments on the interaction of finite-amplitude compression and expansion waves with a shock wave stabilized in a diffuser. These experiments are related to a phenomenon encountered on supersonic-aircraft engines. The apparatus consisted of a convergent–divergent nozzle connected via a duct and a control nozzle to an exhauster. The finite waves were generated at the control nozzle and travelled against the direction of the flow towards the divergent section of the test nozzle, where they interacted with the shock wave. After the interaction, the shock wave was stabilized at another position in the test nozzle. Schlieren photographs were recorded by a high-speed ciné camera, and from these the distance–time trajectory of the shock wave was derived. It was shown how the shock wave's motion depended on the disturbance rise time and on the diffuser angle.

5. Concluding remarks

The meeting ended with a general discussion during which several ideas for further research were put forward.

(i) The propagation of shear within an oscillating turbulent boundary layer should provide a means of investigating turbulence.

(ii) Most of the papers on boundary layers and heat transfer dealt with laminar flow and it was felt that emphasis should now be placed on turbulent flows, since in many practical cases the flow is turbulent.

(iii) The heat-transfer mechanisms near the end wall of a resonance tube and of a Hartmann–Sprenger tube are understood only partially, so that further experimental and theoretical work on this subject would be welcome. Knowledge of these mechanisms would permit the determination of the equilibrium temperature in this region.

(iv) Further work on *open* resonance tubes, is needed to correlate theoretical and experimental results.

(v) New measurement techniques which do not perturb the flow such as laser and ultra-sound anemometry should provide a good means for studying local properties in complicated flow conditions. However, some care is needed with these techniques and further work on their applicability to unsteady flows is required.

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