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Gdańsk, 24 - 27 września 1974 r.

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on

STEAM TURBINES OF GREAT OUTPUT

Gdańsk, September 24 - 27, 1974

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III НАУЧНАЯ КОНФЕРЕНЦИЯ

на тему

ПАРОВЫЕ ТУРБИНЫ БОЛЬШОЙ МОЩНОСТИ

Гданьск, 24 - 27 сентября 1974 г.

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ALLEN SMITH

Great Britain*

Wilson Point Experiments in Turbines

Nomenclature

A — bleed line area,
a — orifice area of bleed nozzle,
C — calibration factor,
C_D — drag coefficient,
d — droplet diameter,
e — Naperian base,
i — complex operator $\sqrt{-1}$,
K — scattering area coefficient,
k — constant,
l — length of light path through vapour,
m — bleed mass flow,
P_T — total head pressure,
P_S — static pressure,
P_D — datum static pressure,
P_p — probe pressure,
q — resultant velocity of drop relative to vapour flow,
r — polar coordinate radius,
Re — Reynolds number based on droplet diameter and slip velocity,
T_T — total head temperature,
T_S — static temperature,
t — time,
U — vapour velocity far upstream,
u — horizontal component of vapour velocity,
u_1 — horizontal component of droplet velocity,
V — velocity in bleed line,
V_{dry} — photocell voltage (dry steam),
V_{wet} — photocell voltage (wet steam),
v — vertical component of vapour velocity,
v_1 — vertical component of droplet velocity,
w — wetness fraction,
w_m — arithmetic mean wetness fraction,
x — horizontal coordinate of droplet,
y — vertical coordinate of droplet,
z — actual flow plane $z=x+iy$,
α — wetness loss correction factor

$$\eta_w=\eta_d(1-\alpha w_m),$$

ΔP — bleed pressure correction,
η_d — dry total head isentropic efficiency,
η_w — wet total head isentropic efficiency,
θ — polar coordinate angle,
λ — wavelength,
σ — scattering coefficient,
ρ_s — density of steam,
ρ_w — density of water,
ω — image plane of transformation

$$\omega=\left(z+\frac{1}{z}\right)$$

1. Introduction

Supersaturation in steam as it expands below the equilibrium saturation line is characterised by subcooling of the vapour to a temperature below the saturation or equilibrium value associated with the prevailing local pressure.

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In a "spontaneous" or "self" nucleating process, nucleation centres are formed from random molecular groupings during the expansion, the rate of their formation being governed by the degree of subcooling of the vapour. When the intensity of condensation, resulting from the combined rates of nucleation and deposition on existing nuclei, rises abruptly to a level which effectively relieves subcooling, then reversion is said to have taken place, this often being referred to as the Wilson Point.

Several investigators have shown experimentally that this physical description of spontaneous nucleation is valid for convergent divergent nozzles, moreover, the ultimate number and size of the water droplets in turbines has also been associated with such a process, although no direct experimental evidence is available from turbines to support this assumption. Fears of excessive blading damage, as well as loss in efficiency, however, especially in those turbines supplied with near saturated steam from water moderated reactors, have sustained an intense interest among turbine manufacturers to understand and evaluate the influence of supersaturation.

2. Early experiments

Supersaturation was largely identified with nozzles and cloud chambers until 1918 when an article by Martin [1] suggested that the expansion below the saturation line in a turbine would more closely follow a supersaturated condition, than an equilibrium wet one, the implication being that design methods should be changed to accommodate this. A meeting followed at Heaton Works between Professor Callendar of steam tables fame and Sir Charles Parsons which resulted in the initiation of an experimental programme, the first part being directed at nozzle experiments and the second at turbine trials [2].

The nozzle experiments (Fig. 1) showed that reversion could be suppressed by applying a high-voltage corona discharge across electrodes, the visible effect being to induce early fog formation at the nozzle discharge. This can be explained by ionization increasing the rate of formation of nuclei thereby promoting earlier reversion. From this result it was reasoned that if saturated steam was ionized at entry to a turbine, the thermodynamic change from a supersaturated to equilibrium expansion would result in an increase in work output, thereby checking Martin's theory.

Ionizing electrodes were subsequently installed in an enlarged entry pipe to a 100 kW turbo-dynamo (Fig. 2) fed with dry steam supplied through a centrifugal steam separator. No change in speed, output, or pressure levels could be detected, however, when discharges of up to 50 kV were employed using both AC and rectified DC supplies.

After modification to both steam supply and electrodes proved ineffective, C.T.R. Wilson was consulted, who challenged the purity of the steam to the turbine, suggesting that it already carried sufficient dust nuclei to inhibit supersaturation. Further nozzle tests were consequently initiated in which aluminium and silica dusts of varying grades were injected upstream into the steam but these appeared incapable of visibly suppressing supersaturation. In the light of today's knowledge this result would not be entirely unexpected since the size of the injected particles would be large and relatively few in number as compared with the huge rate of production necessary to revert the steam($>10^{20}$ per sec per m^3).

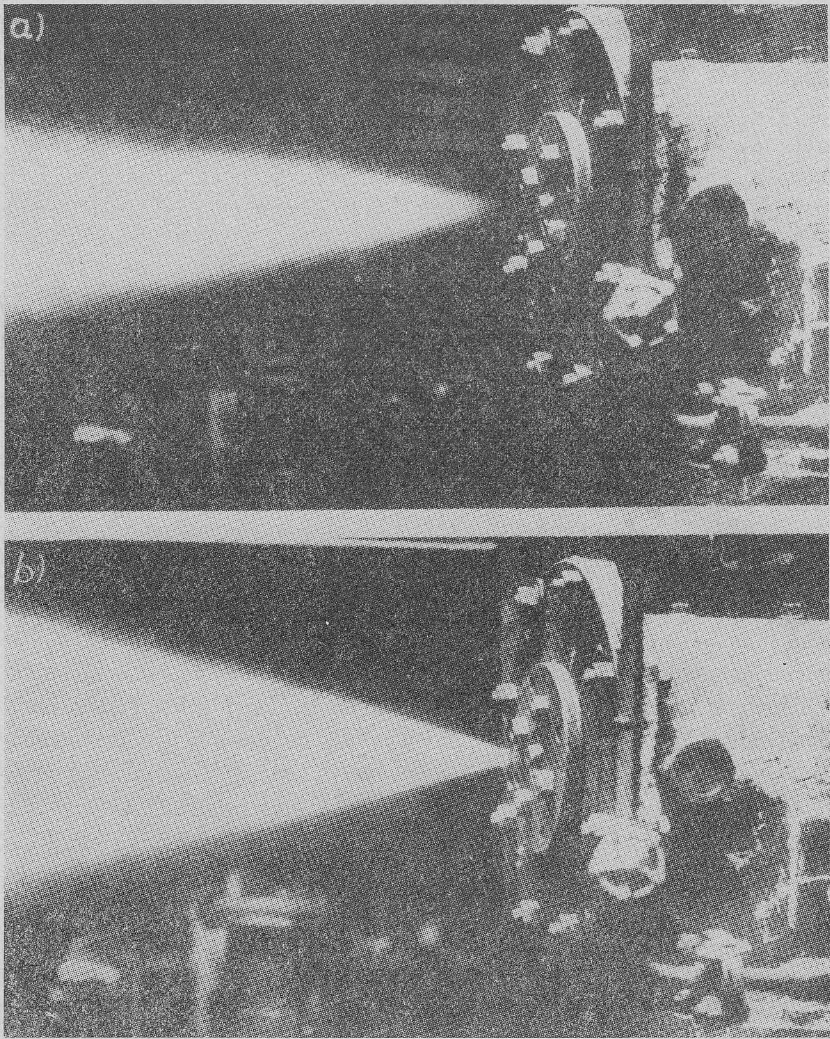

Fig. 1. Condensation induced in a nozzle by high-voltage ionization; a) without ionization, b) with ionization

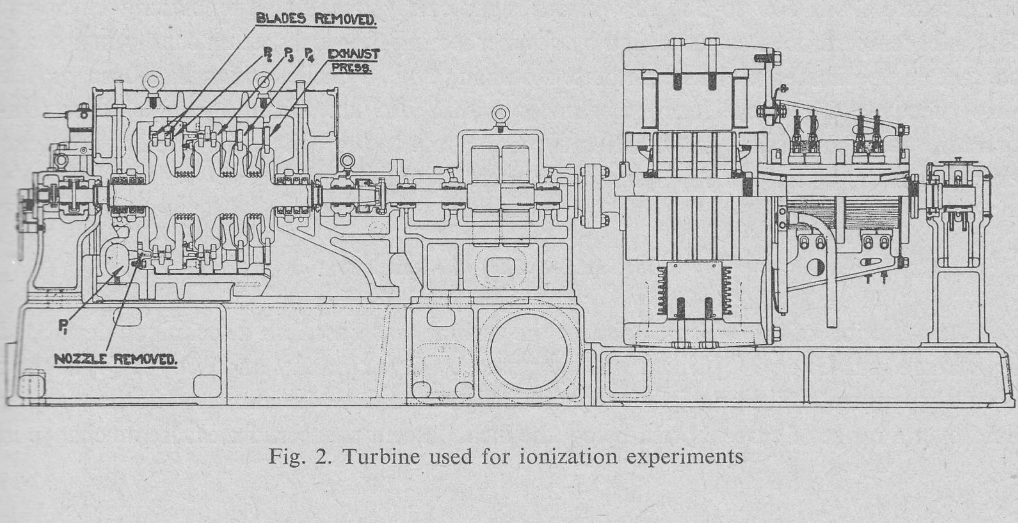

Fig. 2. Turbine used for ionization experiments

The experiments were concluded by ionizing the steam inside the nozzle by electrically-heated incandescent wires, and, although this method was said to be successful in suppressing supersaturation, it was not extended to the turbine.

In retrospect, these early supersaturation experiments appear crude, but nevertheless they did serve to consolidate an equilibrium thermodynamic design basis for wet steam turbines.

3. Model L.P. turbine experiments

Interest in supersaturation waned for many years because of the progressive reduction in wetness in turbines resulting from higher superheat and the adoption of reheat, but was abruptly revived when it was suggested that the erosive attack of water droplets on high-speed low-pressure blading for 500 MW turbines would have a catastrophic influence on blade life. Although interest was rekindled just as much at Heaton Works as elsewhere by this prediction, the true motivation for this second set of experiments stemmed from the use of one-third scale model L. P. turbines to predict the aerodynamic performance of full-scale machines. These models were supplied with steam at their design condition, the shaft speed being three times the full-scale value to duplicate the working Mach number across the blading. Rates of expansion were consequently three times greater than full scale which theoretically tended to support higher supersaturation levels in the model, with the possibility of changing the thermodynamic behaviour of the steam and blading performance.

A three-stage low-pressure turbine was used for the experiment modelling to one-third scale the last three stages of a Ferrybridge 'C' 500 MW machine which employed 3.45 m tip diameter last row blading (Fig. 3). The shaft output was dissipated in a directly coupled hydraulic dynamometer, torque loading being used to control speed to 9000 rpm, three times the full-scale design value. Steam consumption was assessed from the time taken for the condensate to fill tanks of known capacity.

For this particular experiment the inlet and outlet pressures of the turbine were controlled to 0.76 and 0.045 bar respectively, which enabled the terminal condition of the steam to be varied from a dry to a theoretically wet condition by decreasing the steam inlet temperature from 560 to 380 K without significantly changing the blading efficiency. The inlet temperature was controlled by desuperheating the works steam supply in a direct contact desuperheater of the steam blast atomizing type, a design which had been proved very effective with overall energy balances within 2 kJ/kg. Limited control over temperature was also possible by adjusting the firing rate to the boiler, but stability problems arose when the boiler was supplying other users.

Development of hot wire technique

The detection of the Wilson Point in the turbine was based on a technique developed by Binnie and Green [3] which was later used by Gyarmathy and Meyer [4] in their nozzle experiments. The principle is to electrically heat a fine wire immersed in the working fluid over a range of currents well below the incandescent range and measure its change in

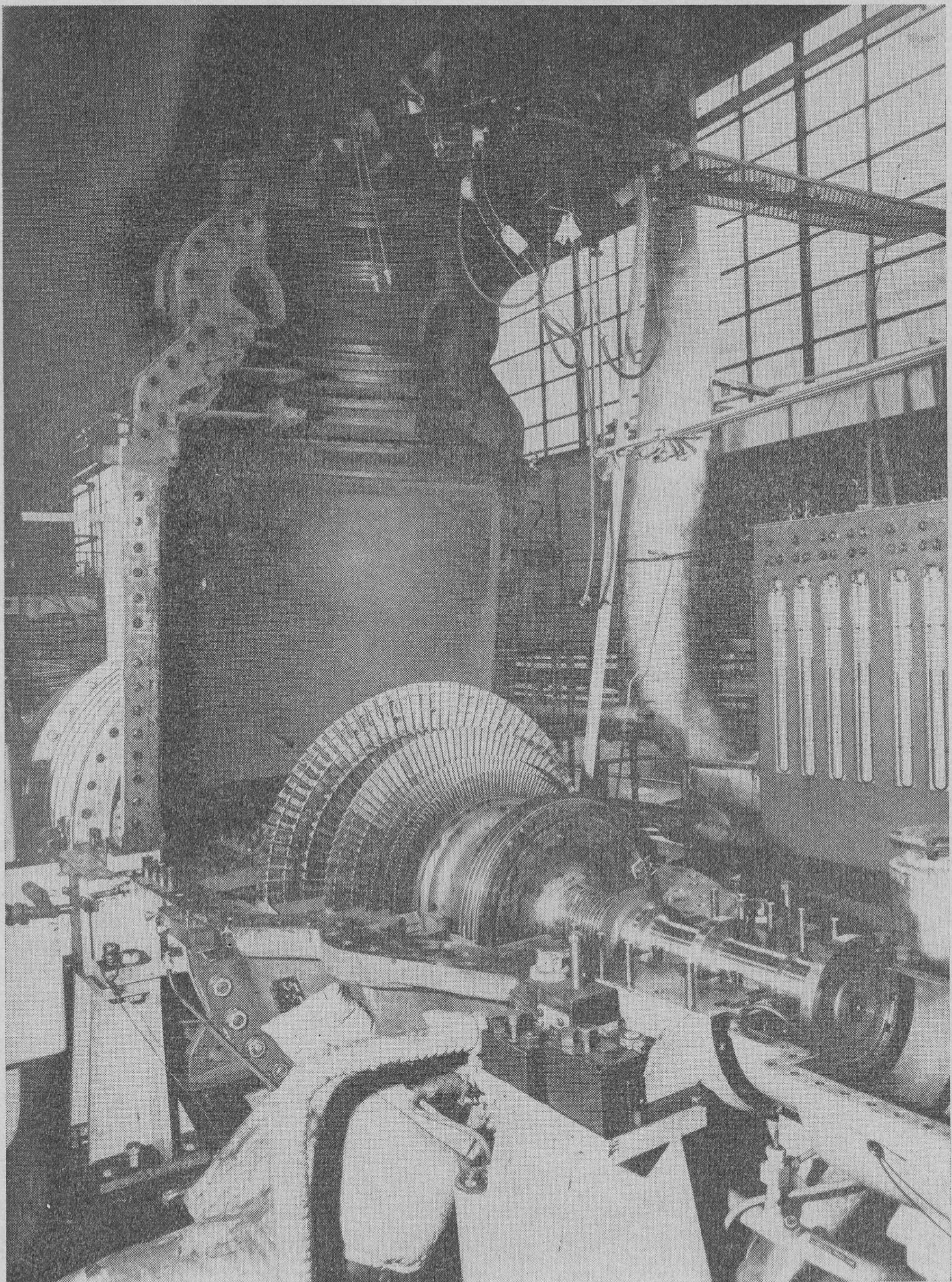

Fig. 3. Model L.P. turbine

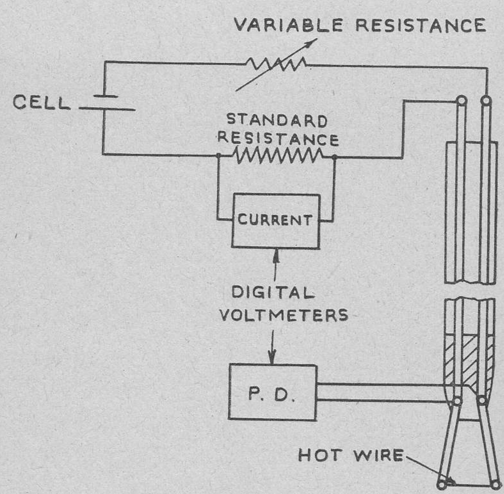

Fig. 5. Hot wire resistance measurement

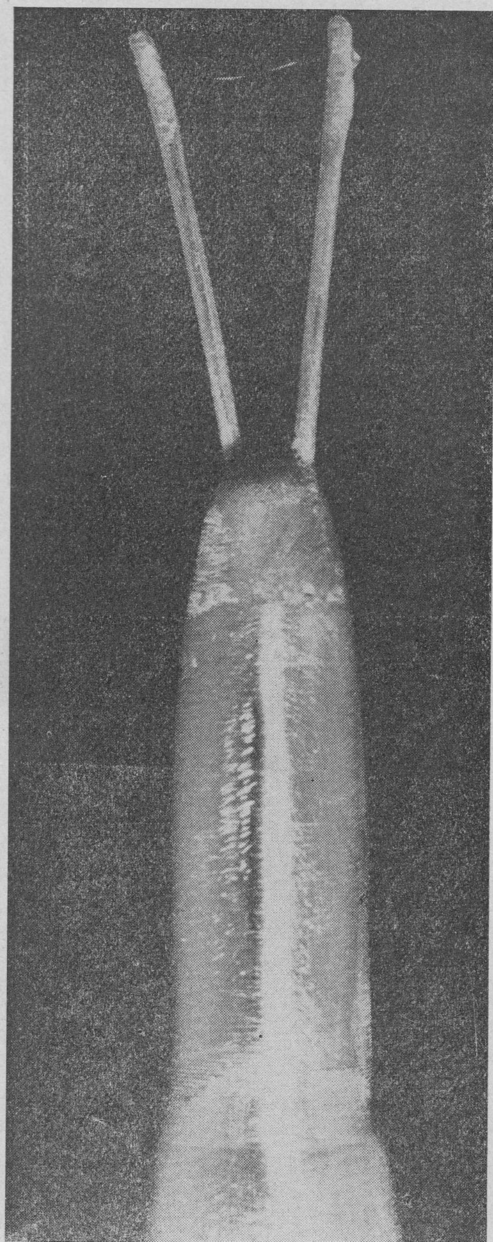

Fig. 4. Hot wire probe

resistance. In dry steam, the resistance rises continuously as the wire temperature increases with current, but in wet steam, evaporation of surface moisture initially prevents the temperature and the resistance rising until the heat input is more than sufficient to evaporate the water reaching the surface. By comparing the shapes of the resistance v. current characteristics, Binnie and Green contended that not only could dry steam be distinguished from wet steam, but that measurements taken in the supersaturated zone of a nozzle had similar resistance characteristics to dry steam. Proof of the instrument being in the supersaturated zone was based on an axial traverse along the centre line of the nozzle in which the position of change in resistance characteristic was found to agree with a local pressure discontinuity registered on wall static tappings.

The hot wire for the first C.A.P. probe was constructed from 50 μm diameter tungsten wire, which, from trajectory calculations based on the Langmuir drag relations, was theoretically capable of intercepting droplets of 0.07 μm diameter at the prevailing steam conditions (Appendix 1). This wire was spot welded to low resistance copper supports, making compensation for internal lead resistance unnecessary and also providing the necessary ductility to enable them to be fused into glass to form a pressure-tight seal.

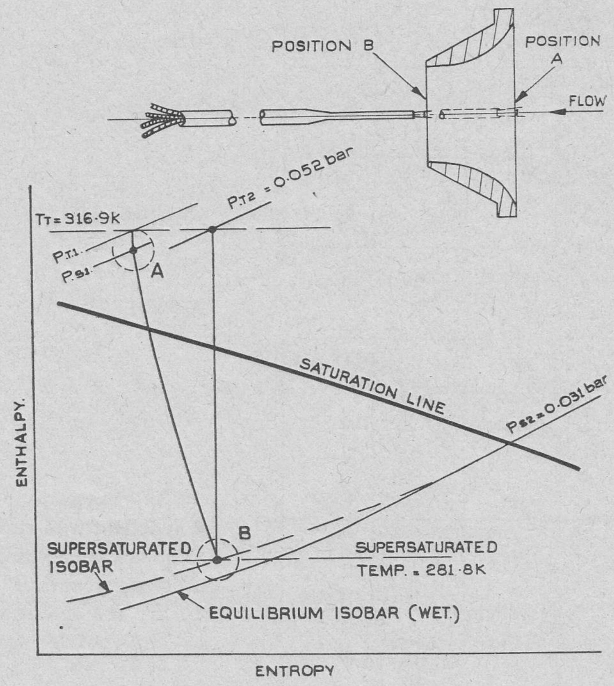

Fig. 6. Nozzle traversing positions and expansion diagram

Trials were made in a convergent nozzle in a steam tunnel to establish the viability of this hot wire technique and, although the shapes of the resistance curves were basically as predicted, initial reductions in resistance proved difficult to explain. These were attributed initially to oxidation of the wire but later to thermo-electric or galvanic effects at the welded junctions. There followed numerous attempts to correct this difficulty, the plain tungsten wire being replaced by gold-plated tungsten wire, to improve the junction. Ultimately, however, the copper supports with the glass seal were abandoned in favour of stainless steel passing through araldite. The final probe (Fig. 4) employed a 13 μm diameter plain tungsten wire, which increased its resistance by a factor of 15 over the original instrument thereby improving its sensitivity by reducing the size of detectable droplets and improving resistance changes. It was necessary, however, to weld two additional leads to the stainless-steel supports close to the tungsten wire junctions so that errors resulting from their relatively high resistance could be avoided. Although Binnie and Green had chosen a double Kelvin Bridge to measure resistance because of its high intrinsic accuracy, it was found more satisfactory to deduce the wire resistance from Ohms law by measuring its potential drop and heating current by digital voltmeters (Fig. 5). This method gave high measurement sensitivity at low heating currents where the gradient of the resistance characteristic was vital.

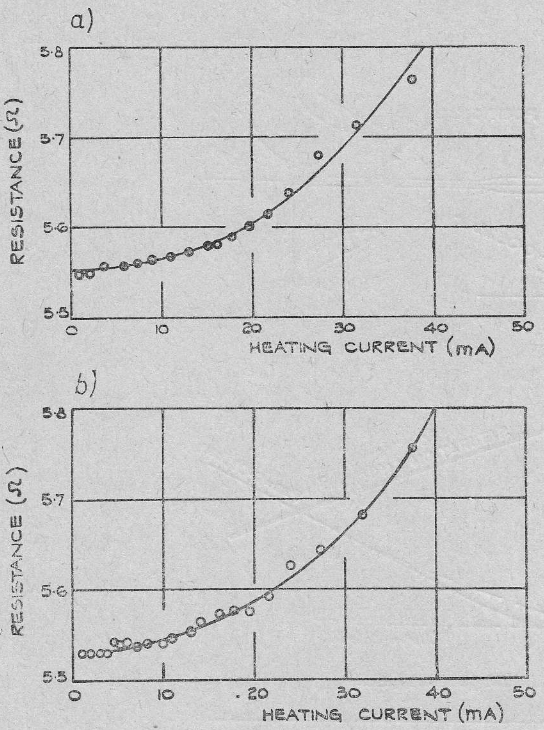

Fig. 7. Hot wire resistance characteristics from convergent nozzle; a) dry characteristic upstream of nozzle—position *A*, b) dry characteristic in metastable zone at nozzle throat-position *B*

Steam conditions in the tunnel were close to those in the turbine exhaust (Fig. 6), the expansion ratio being initially exaggerated to a near critical value to promote subcooling. The theoretical undercooling was 15.7 K corresponding to a supersaturation level of 2.76 at exit, the velocities remaining subsonic as in the turbine to avoid re-evaporation influences of a bow wave shock that Binnie and Green had been obliged to consider in their supersonic experiments. By taking resistance characteristics over a range of axial positions from *A* to *B* (Fig. 6) as the probe was withdrawn through the nozzle, it was found that a dry steam characteristic was obtained throughout (Fig. 7), suggesting either that the steam had not reached the Wilson Point or that water droplets were being deflected past the wire.

Further trajectory calculations on the 13 μm diameter wire indicated that the smallest drop likely to be intercepted would be 0.03 μm diameter; calculations based on nucleation theory indicated, however, that the steam had not crossed the Wilson Point in the nozzle.

Turbine measurements

In extending the hot wire technique to the model L. P. turbine, measurements were made behind the last moving blade row because the mean rate of expansion and subcooling potential was at its highest over the last stage. Here pressure ratios were sufficient to generate transonic velocities in the blading, the probe approach velocity, however, remained subsonic so that bow wave shock induced reversion problems were absent. A fixed radial position of 40% of the blade height from the inner diameter was also chosen for the measurements (Fig. 8), this being clear of secondary loss zones and the wakes from the lacing wires or stubs, so that subcooling would not be suppressed by gross inefficiency.

For wetness measurements in the turbine, the hot wire probe had to be capable of being rotated to lie normal to the direction of flow, local measurements of total and static pressure and total temperature also being necessary to determine the terminal condition of the expansion. Both yaw angle and static pressure were obtained from a disc type instrument with separate side tappings (Fig. 9a). Yaw angle was obtained by coupling the side tappings to a manometer so that by rotating the probe to a position where the side pressures were balanced, the flow angle could be read on an externally mounted protractor. Simultaneously, either side tapping reading could be measured to assess the static pressure from a calibration related to the dynamic pressure difference:

$$C=\frac{P_p-P_s}{P_T-P_s}.$$

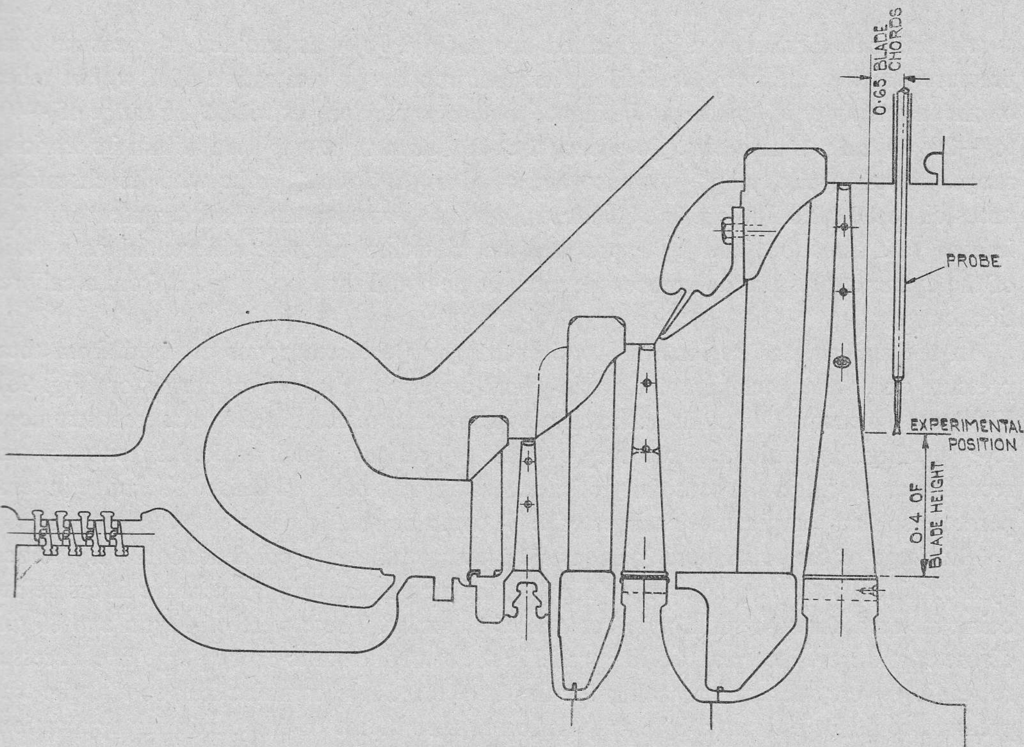

Fig. 8. Cross-section through model L. P. turbine showing measurement position

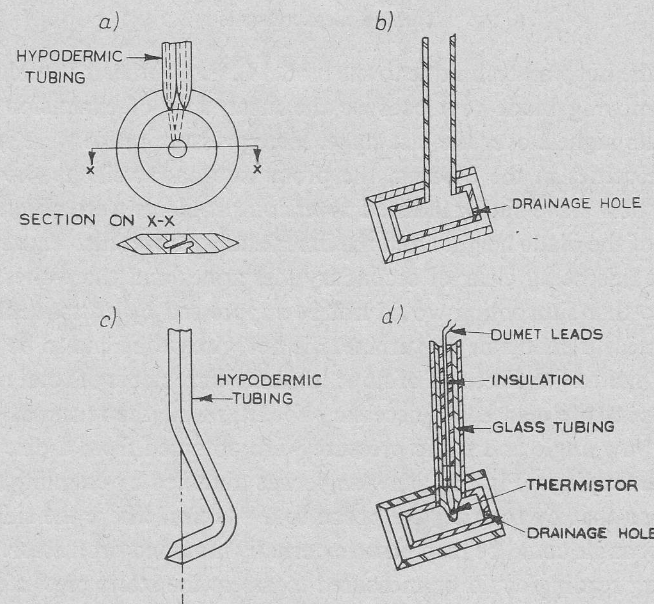

Fig. 9. L.P. turbine instrumentation; a) static pressure and yaw probe, b) total pressure probe, c) pitch probe, d) total temperature probe

An inclined Ermashov [5] shielded probe (Fig. 9b) was adopted to measure total pressure which could be rotated about its stem into the yaw direction of flow, but relied on the insensitivity of its head to incidence to accept pitch angles within the range of $+40°$ to $-20°$ to the machine axis. To ensure that the instrument was used within its working range, however, pitch angle was also measured on a Conrad probe with its chamfered tubes disposed radially (Fig. 9c). The test procedure was to rotate the instrument into the known yaw direction, and by expressing the measured pressure differential as a ratio of the dynamic pressure difference, the pitch angle could then be obtained from a calibration curve.

In the superheated region, the total enthalpy of the steam was assessed from total pressure and a total temperature probe which employed a sensitive thermistor (Fig. 9d). This was also enclosed in an Ermashov head, in the same manner as the pressure instrument, to ensure high dynamic head recovery over the full range of pitch angle. Its resistance was recorded on a bridge, the sensitivity of the measurement being 18 Ω for 1K change in temperature so that temperature changes of 0.1K could be readily detected.

Blockage of the small bore hypodermic pressure tubes by condensation was avoided by a continuous air purging system (Fig. 10), the air passing through ceramic filters before being metered through small nylon spinnerette nozzles. These were of 40 μm and 80 μm diameter and were incorporated in parallel in the total and static probe purge lines. Pressure readings were subsequently taken for the three bleed rate combinations so that the true pressure could be estimated by extrapolation to zero bleed. In this particular application, moreover, the pressure ratio over the orifices exceeded the critical value, so that the pressure

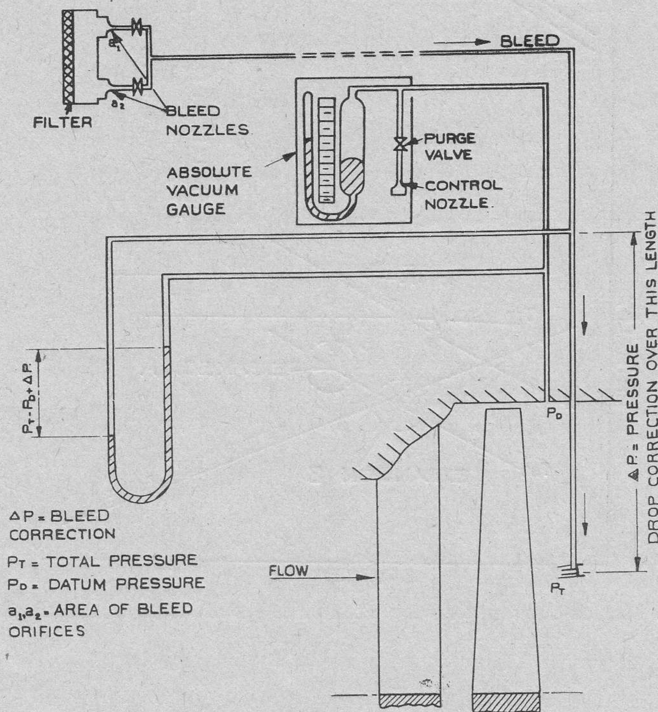

Fig. 10. Continuous bleed system

readings varied linearly with area (Appendix 2); the redundant third reading consequently served as a check on whether the probe had remained unblocked. In the case of the pitch meter, however, only a single bleed to each tube was found necessary, the instrument being checked for blockage with the turbine at rest before and after each test by observing whether the differential manometer levels remained nulled.

Results

Readings were initially taken with the turbine inlet temperature sufficiently high to maintain a superheated static enthalpy condition at the probe position behind the last blade row (Fig. 11, Expansion *A*) and as expected, a dry resistance characteristic was recorded (Fig. 12, Expansion *A*). The inlet temperature was subsequently reduced in stages until the total head enthalpy at the turbine exhaust lay above the equilibrium saturation line and the static enthalpy just below as in the nozzle (Fig. 11, Expansion *B*). Unlike the nozzle, however, the turbine recorded a wet characteristic (Fig. 12, Expansion *B*) suggesting that the Wilson Point had at least been locally exceeded.

Calculations based on the mean expansion rate through the blading indicated no significant increase in the condensation rate, by far the larger proportion of the nuclei having a critical diameter of 0.004 μm. This suggests that the probe should have recorded little evidence of water with its minimum capture diameter of 0.03 μm. (A recalculation based

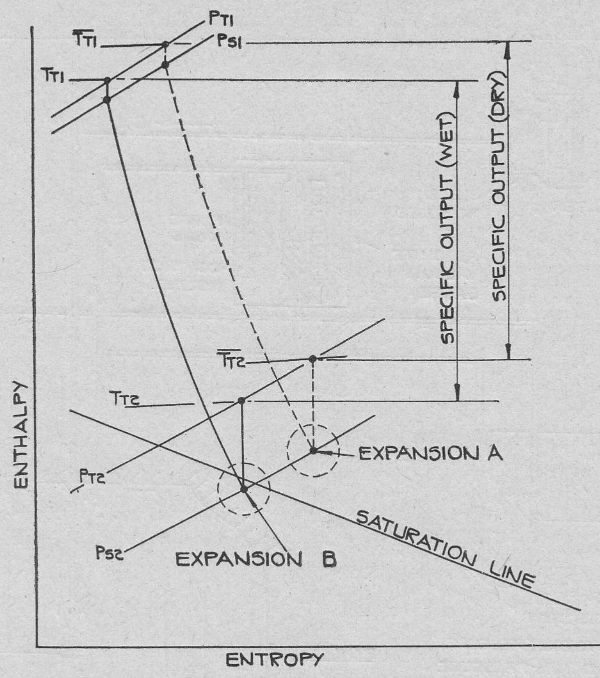

Fig. 11. Mollier diagram showing terminal states of steam from L.P. turbine

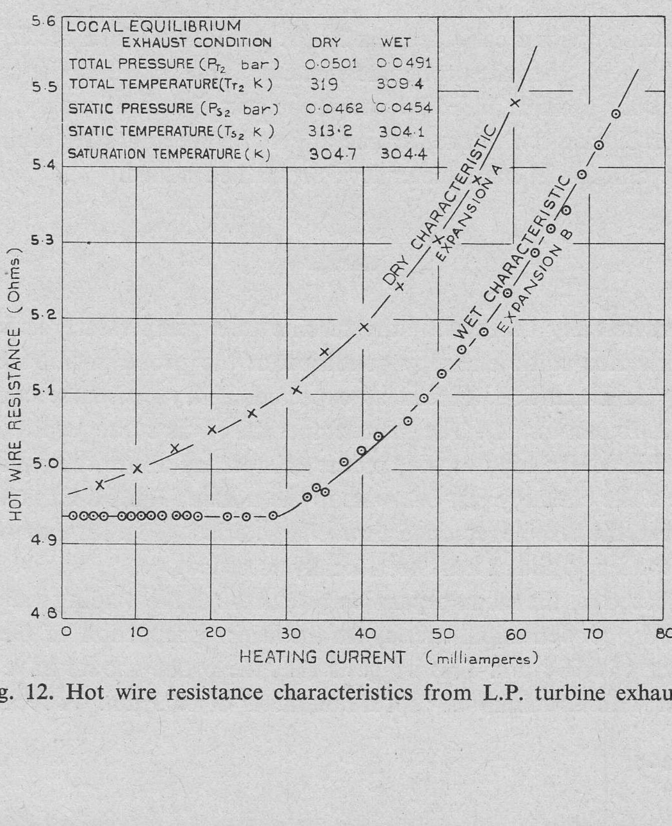

Fig. 12. Hot wire resistance characteristics from L.P. turbine exhaust

on an isentropic flow condition is to be conducted to establish whether the Wilson limit can be exceeded close to the convex blade surfaces where initial accelerations are higher than average).

Although this experiment proved disappointing in not providing positive evidence of high degrees of supersaturation, the flow patterns from model traverses were found to be similar to those of the full-scale machine when velocities were deduced on an equilibrium thermodynamic basis.

4. Model H.P. turbine experiments

Recent investigations at Parsons have been principally directed at improving water extraction rates and understanding the mechanism of wetness losses in those turbines supplied from water moderated reactor systems. In these systems saturated steam is produced at pressure levels ranging from 40 to 70 bar so that the steam enthalphy falls below the peak saturation level. Before entry to the H.P. turbine, the steam is therefore throttled to a slightly wet condition and if no measures were subsequently taken to extract moisture and reheat the steam between the H.P. and L.P. turbines, the terminal wetness would exceed 20%.

To avoid erosion damage and excessive wetness losses, it is consequently necessary to remove as much moisture as possible during the expansion, the designer usually being content to remove damaging free water from circumferential cylinder belts in the restricted axial length of turbine, relying on larger and more sophisticated external separators between the turbines to remove droplets as well as free water.

The effectiveness of water removal from cylinder belts is largely dependent on the state of the water, whether it exists as a fine fog, or the droplets have grown to a size where they can be inertially collected as films on blade surfaces and subsequently reatomized as second generation droplets from the trailing edges. Effective removal becomes more difficult in H.P. turbines because fewer large second generation droplets exist and the higher steam density exerts a higher drag for a given steam velocity so that the droplets tend to remain steam borne, and are not centrifuged from moving blade surfaces to the cylinder walls as free water where they can be drained.

Description of equipment

To study these high-pressure extraction problems a fourteen-stage 50% reaction turbine was built (Fig. 13), the design of the blading fulfilling three distinct functions. The first five stages have the same rate of expansion parameter ($\dot{P}$) [6] as the H.P. turbines of the 540 MW machines supplied for the Pickering Candu type PWR system, with the intention of reproducing the nucleation conditions of the full-scale machine. The following five stages constituted a transitional zone, feeding four detachable stages modelled initially to have similar blading geometry to the Pickering H.P. turbines.

The model was designed for an inlet pressure of 20 bar, which was as high as the Works boilers would allow, the inlet superheat being controlled by an elaborate desuperheating

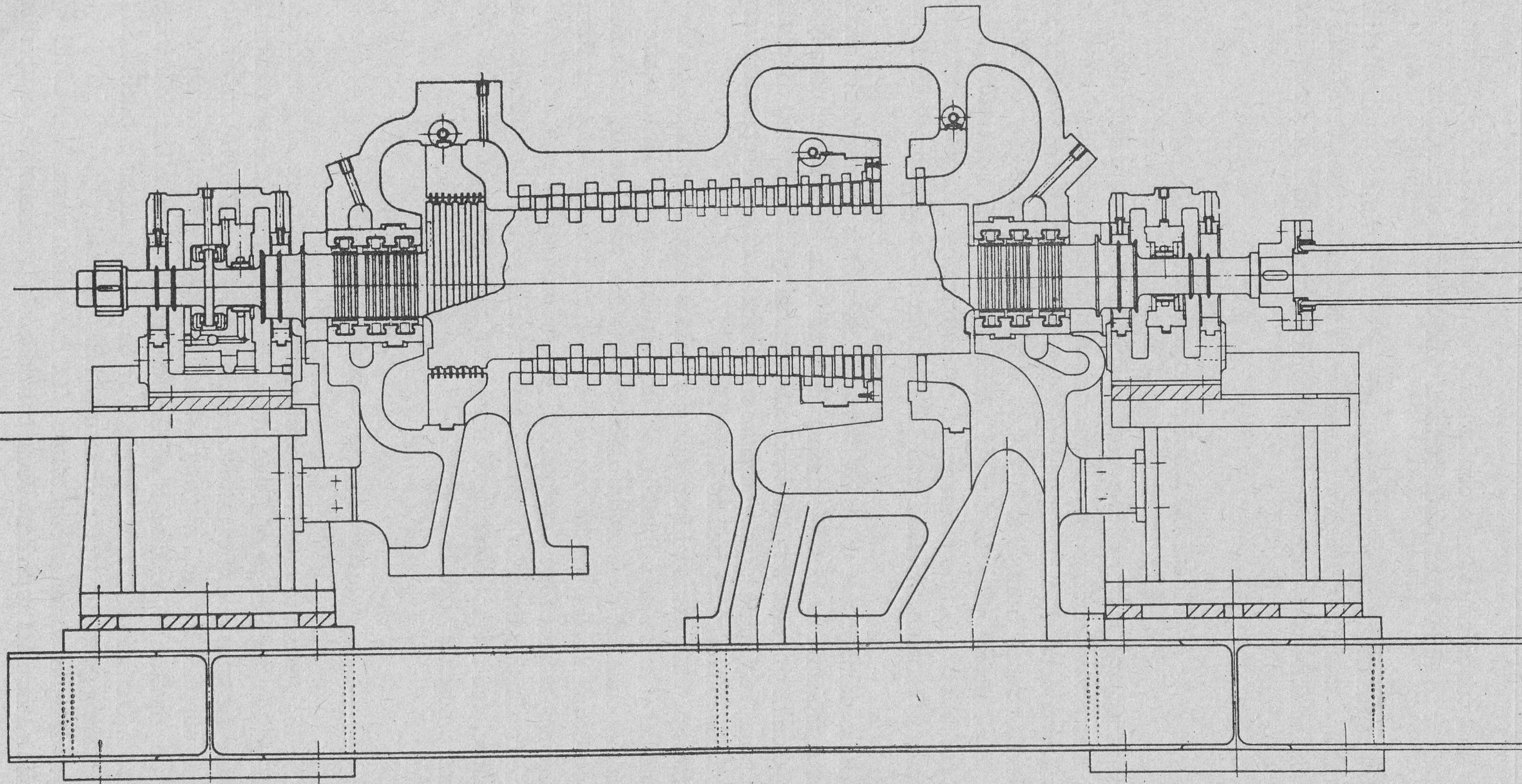

Fig. 13. Cross-section through experimental H.P. turbine

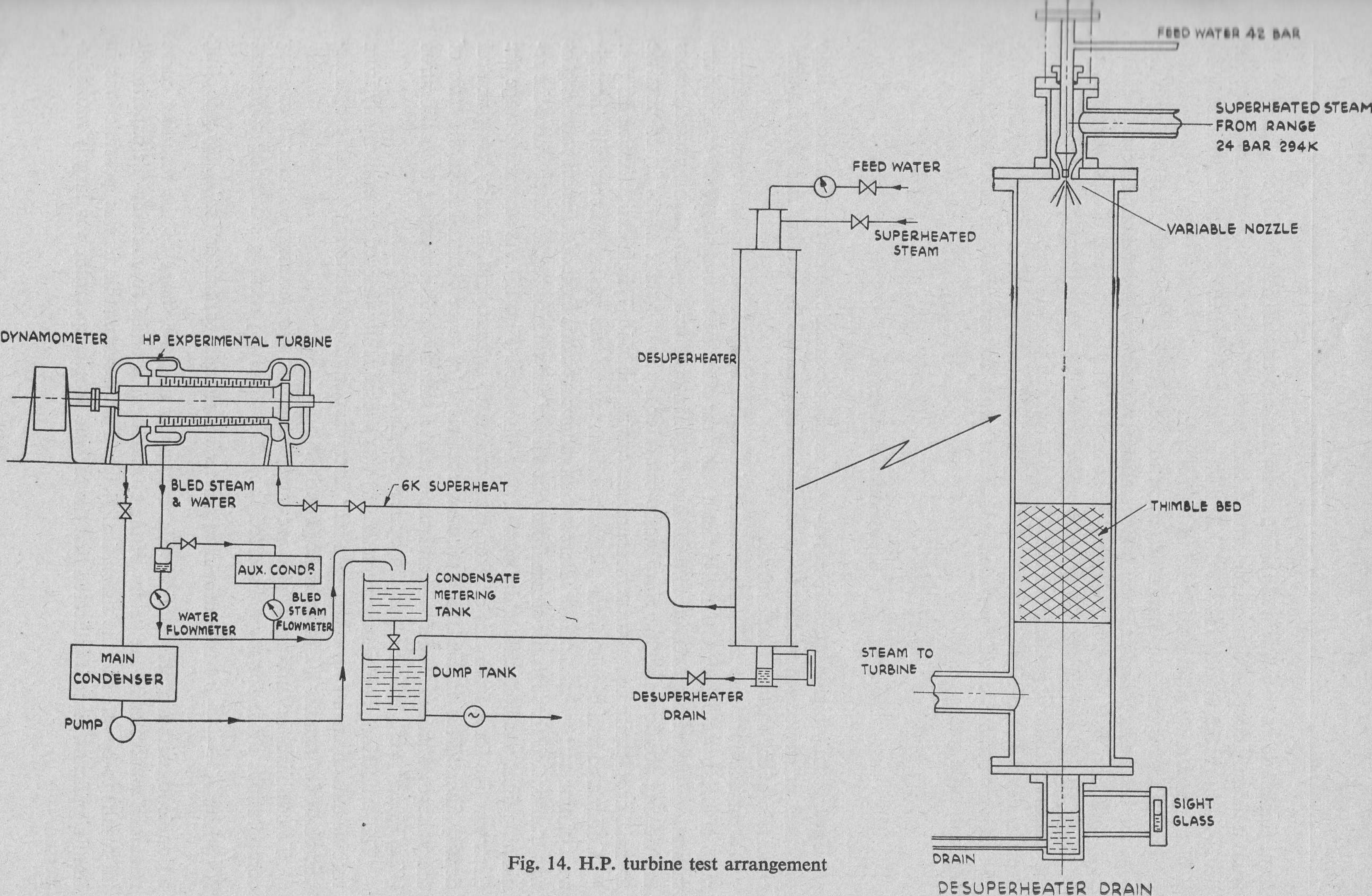

Fig. 14. H.P. turbine test arrangement

arrangement down to 6 K (Fig. 14). The steam was subsequently wetted by extracting work from a directly coupled dynamometer to a condition of 7 bars and 6% wetness before the belt. Although the model was only 1.2 m long between bearing centres, it produced 900 KW at a maximum rotational speed of 10,000 rpm.

Provision was made to change the extraction belt geometry after the last moving blade row, the belt being followed by a further stationary blade row to maintain a representative flow condition past the water extraction zone. No further moving blades were added, however, so that the theoretical wetness before the extraction belt could be assessed from the steam tables having measured the inlet enthalpy, the work done per unit mass and belt pressure. Two sets of sight glasses were also provided along each side of the cylinder cover so that observations could be made through the steam across the top of the shaft between the first seven stages.

Experimental investigation

Unexpectedly high wetness losses as well as poor extraction belt performance at high pressures prompted investigations to establish their causes by establishing the physical condition of the steam in the turbine.

At an inlet pressure and temperature of 8.45 bar and 451 K and an overall pressure ratio of 4.1, it was observed that the steam was clear after the second stage, the equilibrium saturation line having been crossed in this stage. Intermittent wisps of fog passed across the viewing position after the third stage, but after the fourth stage it was found possible to make droplet size and wetness measurements using the Mie [7] light extinction technique.

Collimated white light from a quartz iodine source was passed successively through a set of nine narrow band colour filters so that monochromatic light of different wavelengths was transmitted through the steam from one side of the turbine to the other where the remaining light was collected and focussed on a photocell (Fig. 15). At an earlier stage the electromotive force from this cell had been calibrated against light intensity using neutral density filters. This enabled the extinction coefficient (σ) to be deduced from the ratio of the voltages obtained under wet and superheated steam conditions using the calibration $(V_{wet}/V_{dry})^{5/4}=e^{\sigma l}$, where l was the optical length of the steam path.

The extinction coefficient parameter (σl) was subsequently derived experimentally from turbine measurements for each of the nine filter wavelengths (λ) enabling a double logarithmic plot of σl against $1/\lambda$ to be made (Fig. 16).

To establish the turbine droplet sizes and wetness, it was necessary to refer to existing computations made for monodispersed droplet systems [8] relating scattering coefficient $K\left(\text{where } K=\frac{2}{3}\frac{d}{w}\sigma\right)$ to a droplet diameter/wavelength parameter ($\pi d/\lambda$). By adopting a double logarithmic presentation (Fig. 16) once more, the shape of the resulting curve remained unaffected by the values of the constants d, w and l so enabling the experimental results to be fitted to the theoretical shape. That a reasonable fit was possible was in itself significant, since it indicated that the turbine droplet spectrum was largely monodispersed.

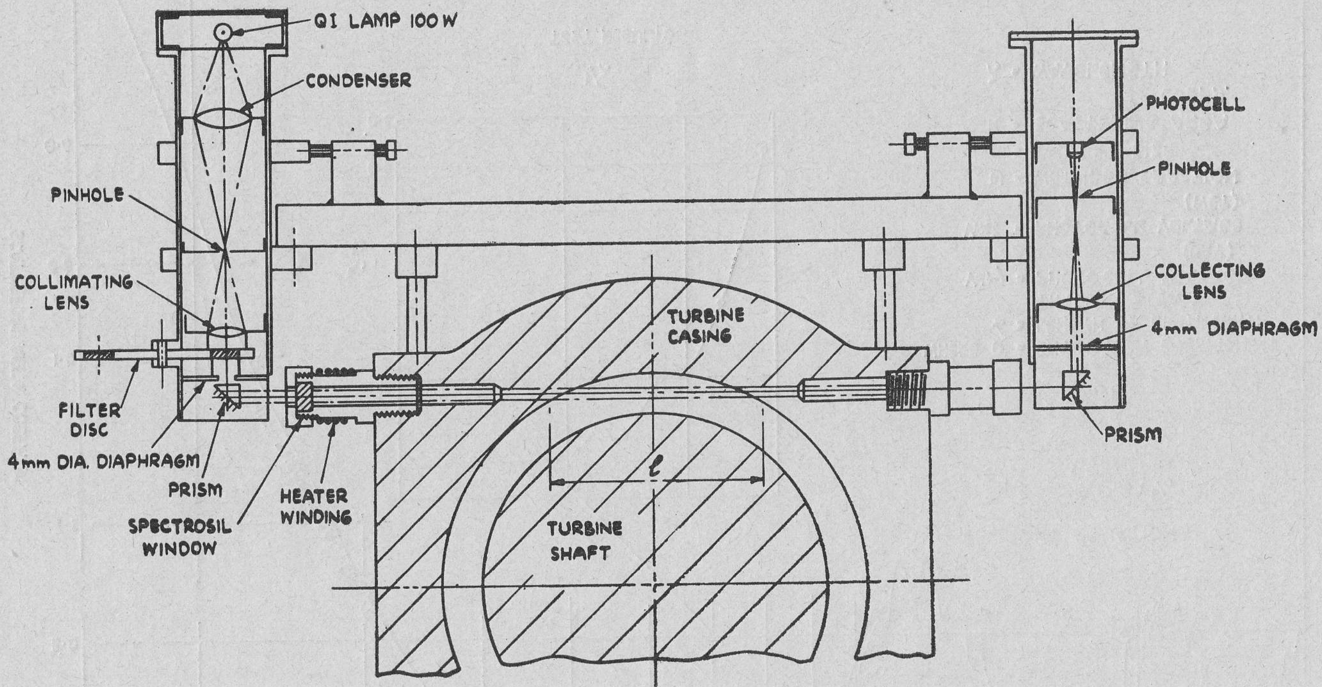

Fig. 15. Light extinction apparatus

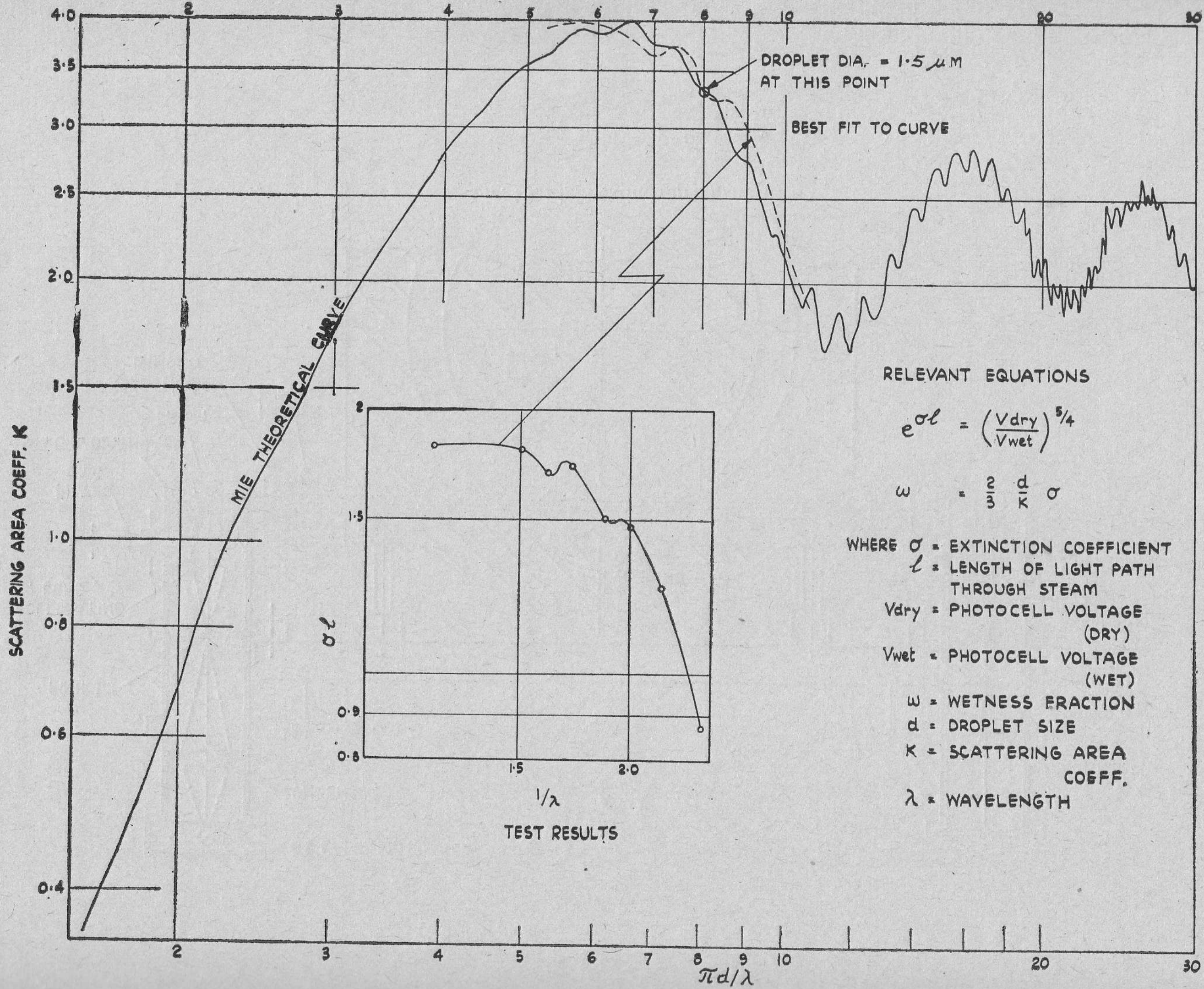

Fig. 16. Determination of droplet size

A droplet size of 1.5 μm was subsequently established from the value of the abscissa on the theoretical curve, knowing the experimental wavelengths. The corresponding wetness was calculated to be 0.1 % as compared with the equilibrium value of 1 %.

Instead of the light becoming suddenly opaque in the turbine, as observed in H.P. nozzle experiments [9], progressive diminution of the light transmission took place until the density of the fog completely obscured vision after the sixth stage. It would therefore appear that, instead of the intensity of condensation rising abruptly as in a nozzle to give a reasonably well-defined Wilson point, progressive condensation takes place over a number of blade rows in a turbine.

These observations would agree with a suggestion by Moore [10] that vapour close to the convex blade surfaces is subjected to a considerably higher initial expansion rate than average and may consequently reach its Wilson limit earlier. The vapour in the remainder of the blade passage however would suffer less severe rates of expansion so that it may remain subcooled to varying degrees until it passes sufficiently close to the suction surface of blading in a following row to suffer reversion. A process is consequently envisaged where successive reversions take place, until supersaturation has been effectively relieved throughout the flow.

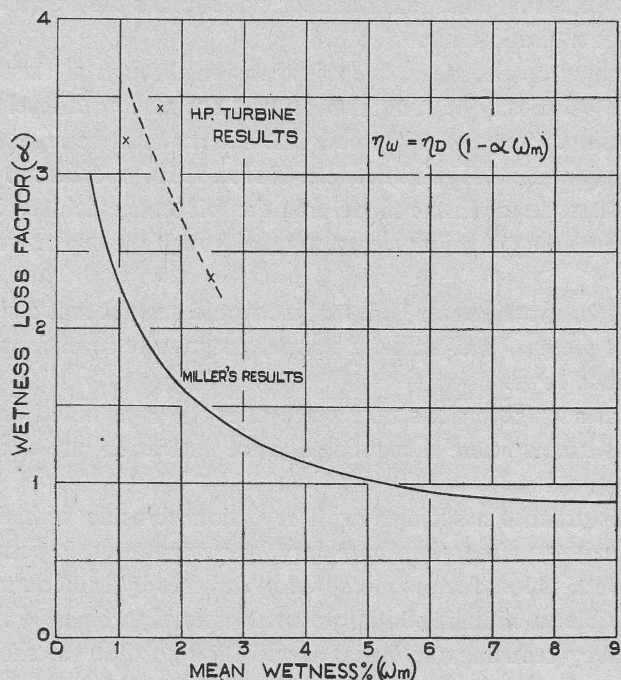

Fig. 17. High-pressure wetness loss factors

It is possible that the sudden pressure change associated with reversion may be superimposed on the adverse pressure gradient created by the suction surface deceleration towards the blade trailing edges, the combination being sufficient to induce boundary layer separation. Should such separation extend over several blade rows, then the high wetness loss coefficients measured by Miller [11] and ourselves (Fig. 17) would be explained. A remedy would therefore be to aerodynamically unload the blades by reducing the initial acceleration and subsequent diffusion of the steam on the suction surfaces so as to render the boundary layer immune to the combined reversion and diffusion influences of the steam.

Unfortunately, progressive reversion does not necessarily help to explain the low water extraction rates in H.P. turbines since the droplet size is linked to the degree of supersaturation present before reversion. If, however, the rates of expansion on the suction surface were controlled, it may be possible to alter the degree of supersaturation or subcooling and thereby influence initial droplet sizes and their subsequent collection.

5. Conclusions

1. The performance of an early turbine remained unchanged when the steam supply was ionized by electrical discharge. This suggested that, unlike a nozzle, a turbine does not exhibit a significant degree of subcooling, causing Martin's supersaturated design concept to be rejected.

2. Hot wire measurements behind the last stage of an L.P. turbine model indicate the presence of droplets exceeding 0.03 μm in diameter as soon as the exhaust condition falls below the equilibrium saturation line.

3. Calculations based on the mean rate of expansion through the last row of moving blades suggest that the intensity of condensation had not risen to a level which could be identified with reversion. Consequently, these calculations must be repeated to allow for the variation in expansion rate that exists between blades. It is important to note, however, that wet steam traverses made in the model and the full scale machine yield comparable flow patterns assuming an equilibrium steam state, although the expansion rates differ by a factor of three.

4. Evidence from an experimental H.P. turbine would suggest that a significant degree of supersaturation is present, but, unlike a nozzle, progressive reversions appear to take place over several blade rows.

5. It is likely that such reversions take place after the high initial acceleration close to the blade suction surfaces where subcooling and the nucleation rate would be at its highest.

6. Should the disturbance associated with reversion coincide with a high diffusion rate on the blade suction surface, then boundary layer separation is possible which may explain high initial wetness loss factors measured in turbines by Miller and ourselves.

7. It may be possible to minimize initial wetness losses in turbines by reducing suction surface loading, thereby reducing the initial acceleration so that the subsequent rate of diffusion can be reduced.

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Appendix 1

Determination of the minimum droplet diameter intercepted by the hot wire probe

The problem was reduced to finding the trajectory of a spherical droplet in the flow field around an infinitely long cylinder lying with its axis normal to the flow. The droplet was initially assumed to be travelling with negligible slip in the vapour phase and two-dimensional incompressible flow was assumed around the cylinder, ignoring thermal influences from the wire.

To avoid underestimating the size of droplet intercepted by the wire, the reduction in drag coefficient associated with slip flow (high Knudsen numbers) was deliberately ignored and the Langmuir drag coefficient

$$C_D = \frac{24}{Re}(1 + 0.197 Re^{0.63} + 2.6 \cdot 10^{-4} Re^{1.34}),$$

which had been programmed for other calculations, was retained. It will be observed, however, that at low Reynolds numbers (Re) this relationship reduces to the Stokes form

$$C_D = \frac{24}{Re}.$$

If v and u are the vertical and horizontal velocity components of the vapour phase and v_1 and u_1 the corresponding components of the droplet, then the relative velocity components of the droplet in the vapour are $(v - v_1)$ and $(u - u_1)$. Since drag acts in the direction of the resultant (q) of these relative velocities, we have

$$\text{Drag} = \frac{1}{2} C_D \frac{\pi d^2}{4} \rho_s q^2 \qquad (1)$$

and the components of the momentum equation in the vertical and horizontal directions are

$$\frac{dv_1}{dt} = \frac{3}{4} C_D \frac{\rho_s}{\rho_w} q(v - u_1) \tag{2}$$

and

$$\frac{du_1}{dt} = \frac{3}{4} C_D \frac{\rho_s}{\rho_w} q(u - u_1), \tag{3}$$

where

$$q^2 = (v - v_1)^2 + (u - u_1)^2. \tag{4}$$

The expression $\omega = U(z + 1/z)$ can be shown to transform from a parallel flow field in the image plane (ω) into the flow past a cylinder of unit radius in the actual plane (z), where $z = re^{i\theta}$ in polar coordinates and U is the vapour velocity far upstream.

Velocities in this z plane are given by

$$u - iv = -\frac{dw}{dz} = -U\left(1 - \frac{1}{z^2}\right)$$

$$= -U\left(1 - \frac{\cos 2\theta}{r^2} + i\frac{\sin\theta}{r^2}\right)$$

and by equating real and imaginary parts we have

$$u = U\left(\frac{\cos 2\theta}{r^2} - 1\right) \tag{5}$$

and

$$v = U\frac{\sin\theta}{r} \tag{6}$$

conversion to cartesian form being effected through the relationships $\tan\theta = y/x$ and $r^2 = x^2 + y^2$.

A finite difference calculation can now be made combining equations (2), (3), (4), (5) and (6) to determine the position of the droplet in the z plane after successive discrete time intervals.

To establish the smallest droplet likely to collide with the wire, the calculation was conducted for a series of droplet sizes, the starting position being 5 wire diameters upstream and 0.05 of a diameter above the stagnation streamline. Trajectory plots were subsequently made to establish the minimum droplet diameter to collide with the wire.

Appendix 2

Manometer pressure correction for supercritical constant bleed purge system

If the inlet pressure and temperature to the bleed control nozzles are atmospheric and the pressure ratio supercritical as in the model turbine, then the bleed mass flow will be proportional to the nozzle area, i.e.

$$m = k_1 a \text{ (see nomenclature)}. \tag{1}$$

The bleed velocity in the gauge line be given by:

$$V = \frac{m}{\rho A}, \tag{2}$$

and if laminar flow conditions prevail, then the pressure drop will be proportional to the velocity or

$$\Delta P = k_2 V. \tag{3}$$

Substitution of equation (2) in equation (3) gives

$$\Delta P = \frac{k_2 m}{\rho A} \,. \tag{4}$$

If ρ approximates to the density at discharge, then, by substituting equation (1) in equation (4):

$$\Delta P = k_3 a \,. \tag{5}$$

Under these circumstances, the error in pressure resulting from the bleed is proportional to the nozzle area.

Badania doświadczalne punktu Wilsona w turbinach

Streszczenie

W ostatnich latach wiele prac teoretycznych poświęcono poziomom przesycenia w turbinach i punktowi przecięcia linii ekspansji z linią Wilsona, wpływających na liczbę i wielkość tworzących się kropel wody i ich zdolność wywoływania erozji. Obawa przed uszkodzeniem łopatek i spadkiem sprawności, szczególnie w turbinach zasilanych parą nasyconą, stanowi bodziec do coraz intensywniejszych badań prowadzonych przez producentów turbin w celu wyjaśnienia i oceny wpływu przesycenia na warunki fizyczne panujące w turbinie.

Pierwsze doświadczalne badania tworzenia się zarodzi kondensacji prowadził w zakładach w Heaton, w latach 1921 - 1925, Sir Charles Parsons przy współpracy prof. H. L. Callendara. W badaniach posługiwano się dyszami i turbiną parową; wpływająca para sucha była poddawana jonizacji za pomocą wyładowania elektrycznego. O ile wyniki badań w dyszach wskazywały na możliwość kontrolowania przesycenia przez jonizację, o tyle w działaniu turbiny nie wykryto żadnych zmian.

Drugą grupę doświadczeń przeprowadzono w roku 1972 na modelowej niskociśnieniowej turbinie parowej. Celem ich było ustalenie, czy teoretyczne poziomy przesycenia osiągalne w takim modelu są reprezentatywne dla przepływów zachodzących w turbinie o normalnych rozmiarach. Posługując się metodą cieplno-oporową Binnie i Greena wykryto obecność wody tuż po przekroczeniu linii równowagi nasycenia. Wskazuje to na występowanie załamania się stanu przechłodzenia przynajmniej w części przepływu. Ponadto stwierdzono dalszą zgodność obrazu przepływu w turbinie modelowej z obrazem w turbinie normalnej wielkości.

Ostatnie badania doświadczalne, przeprowadzone w wysokociśnieniowej turbinie na parę mokrą, w których zastosowano metodę ekstynkcji światła dla pomiaru wielkości kropel oraz wilgotności pokazały, że załamanie się stanu przechłodzenia nie jest zlokalizowane w jednym miejscu, tak jak w dyszy, lecz rozciąga się na kilka rzędów łopatek. Stwierdzono, że mgła staje się coraz gęstsza w miarę postępu ekspansji. Zmniejszenie mocy wyjściowej spowodowane tym procesem było znacznie większe niż początkowo sądzono.

Экспериментальные исследования точки Вильсона в турбинах

Резюме

В последние годы многие теоретические работы посвящались уровням пересыщения в турбинах и точке пересечения линии расширения с линией Вильсона, влияющих на количество и размеры образующихся водяных капель и их эрозионную способность. Опасность разрушения лопаток и понижения к.п.д., особенно во влажнопаровых турбинах, является стимулом все более интенсивных исследований, проводимых заводами-изготовителями турбин с целью выяснения и оценки влияния пересыщения на физические условия в турбине.

Первые экспериментальные исследования образования зародышей конденсации проводились в 1921 - 1925 г.г. Сир Чарлесом Парсонсом в сотрудничестве с профессором Х. Л. Каллендаром на заводе в Хитон. В исследованиях пользовались соплами и паровой турбиной. Сухой пар на выходе подвергался ионизации с помощью электрического разряда. Насколько результаты исследований в соплах показывали на возможность контроля пересыщения ионизацией, настолько в работе турбины не обнаружены никакие изменения.

Вторая группа экспериментов была проведена в 1972 г. на модельной паровой турбине НД. Целью этих исследований было определение, являются ли теоретические уровни пересыщения, достигаемые в такой модели, характерными для течений в турбинах натуральных размеров.

Пользуясь термическо-резистантным методом Бинни-Грина, обнаружено присутствие воды сразу же после пересечения линии равновесия насыщения. Это указывает на провал состояния переохлаждения по крайней мере в части течения. Кроме того, обнаружена хорошая сходимость картины течения в модельной турбине с картиной течения в натуральной турбине.

Последние экспериментальные исследования, проведенные во влажнопаровой турбине высокого давления, с применением метода экстинкции света для замера размеров капель, показали, что провал состояния переохлаждения не происходит в одном месте, как в сопле, но распространяется на несколько рядов лопаток. Констатировано, что туман становится все сильнее по мере развития экспансии. Уменьшение мощности, вызванное этим процессом, оказалось значительно большим, чем это можно было раньше ожидать.