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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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DENIS J. RYLEY, KEITH A. TUBMAN

Great Britain*

Spontaneous Condensation in High-Pressure Expanding Steam

Notation

f – friction factor,
h – specific enthalpy,
l – distance along nozzle from inlet,
l^* – distance along nozzle from inlet of Wilson point,
L – nozzle total length,
p – static pressure,
p_0 – reservoir (stagnation) pressure,
p^* – Wilson point pressure,
$\dot{P}$ – expansion rate parameter,
s – specific entropy,
t – time,
T – temperature,
T_0 – reservoir (stagnation) temperature,
x – mass flow dryness fraction.

1. Introduction

The location of the appropriate Wilson Line for steam expanding under defined conditions has been the subject of many investigations (e.g. [1, 2, 3]). Until recently, steam condensed within turbines by self-nucleation only in low-pressure machines, and thus all Wilson Lines published hitherto are located within the low-pressure region (below 3.5 bar). With the advent of the light-water nuclear reactor it is becoming common for the supply steam to the high-pressure turbine to be saturated or marginally wet, as a consequence of which nucleation will occur within this turbine. Hence it has become necessary to provide experimental data on the probable location of condensation within a high-pressure expansion together with the expected size of the fog droplets.

The experiments to be described provide "raw" data for a high-pressure Wilson Line and supplement the limited information published by Gyarmathy *et al.* [4].

2. The nozzle assembly

Figure 1 shows a simplified arrangement drawing of the nozzle assembly. It consisted essentially of two wall blocks (*1*, *2*) (Fig. 1b, c) bolted together without a gasket, one block (*1*) having a continuous longitudinal slot which formed the steam flow passage (*3*) of con-

* Department of Mechanical Engineering, University of Liverpool.

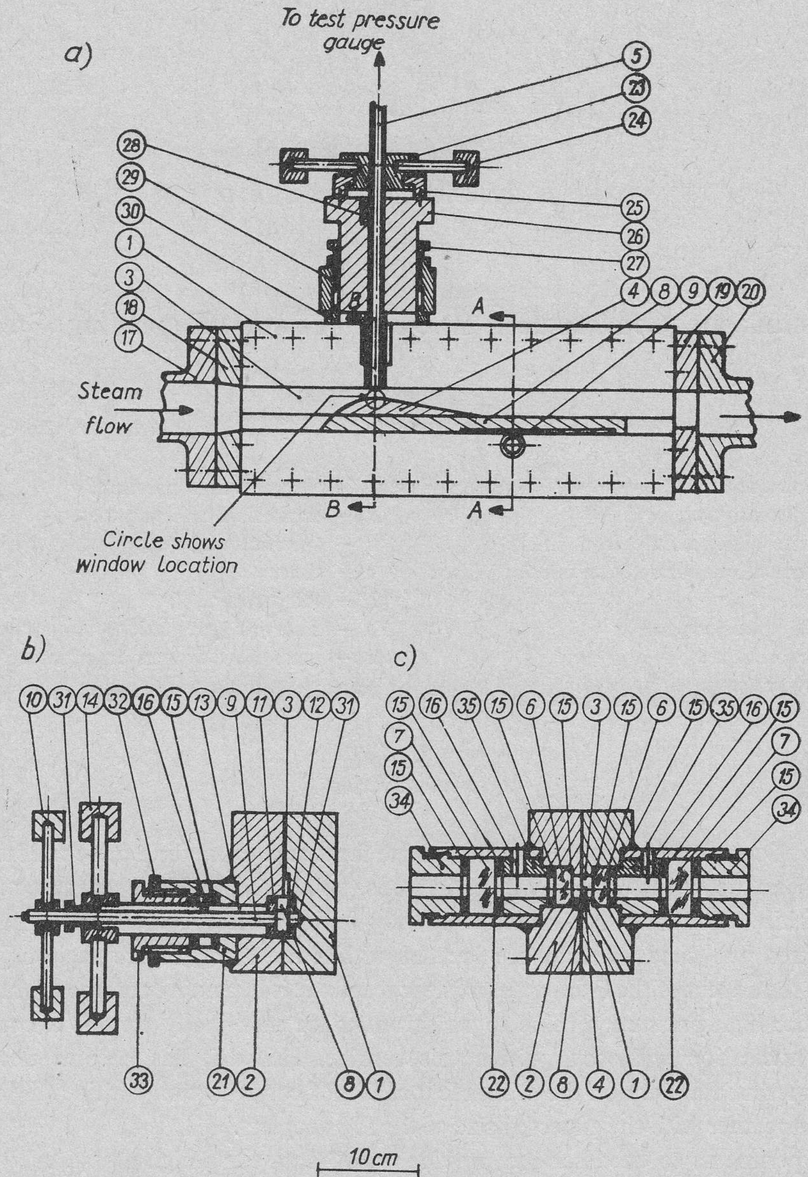

Fig. 1. Simplified general arrangement of the nozzle. a) Cross-section through nozzle showing the static pressure instrumentation. b) Section *AA* – Profile-piece traverse sub-assembly. c) Section *BB* – Nozzle side-windows sub-assembly (instrumentation not shown)

1 – nozzle block, *2* – nozzle block, *3* – steam flow passage, *4* – profile-piece, *5* – sensing device, *6* – viewing windows, *7* – viewing windows, *8* – rack, *9* – pinion and shaft, *10* – shaft handwheel, *11* – outward pressure plate, *12* – inward pressure plate, *13* – shaft sleeve, *14* – sleeve handwheel, *15* – steam packings, *16* – steam leakage spaces, *17* – inlet steam flange, *18* – inlet transition flange, *19* – outlet stopper flange, *20* – outlet steam flange, *21* – traverse housing, *22* – window housing, *23* – instrument traverse nut, *24* – nut handwheel, *25* – nut restraining device, *26* – instrument primary gland, *27* – instrument tertiary gland, *28* – key, *29* – instrument secondary gland, *30* – copper washer plate, *31* – traverse shaft bearings, *32* – locking nut, *33* – traverse gland nut, *34* – window primary gland, *35* – window secondary gland stant width of 8.06 mm. The expansion passage was contrived by the insertion of a movable plate (*4*) so profiled as to form a Laval nozzle. This profile-piece has a radiused entry, but beyond the throat, of height 10.5 mm, the profile was specifically designed to confer upon the expansion a constant value of P of 10^4 s^{-1}. The method employed in achieving this design constraint was due to Gyarmathy and Meyer [3].

The profile-piece could be moved so as to bring any section within the expansion adjacent to the sensing device (*5*) and the viewing windows (*6, 7*). The profile-piece was screwed to an internal rack (*8*) which was propelled along the nozzle body slot by a pinion (*9*) turned by an external handwheel (*10*) (Fig. 1b). During high-pressure operation, the static pressure difference across the profile-piece promoted thereon a strong downstream thrust and a braking device was incorporated to restrain unwanted movement. The brake consisted of two copper pressure plates, (*11, 12*) which, by turning a further external handwheel (*13, 14*) could be pressed into contact with both sides of the pinion and the adjacent sections of the rack.

The location of the profile-piece was indexed by a pointer rotating against an external circular protractor calibrated in degrees. One clockwise degree of handwheel rotation advanced the profile piece 0.0208 mm flow-wise.

Two alternative instrument sub-assemblies were available (Fig. 1a) arranged for mounting on top of the nozzle assembly in order to sense from the ceiling of the flow passage. The sub-assemblies were essentially similar; one provided a facility for measuring static pressures, the other for traversing an impact tube through the complete height of the flow. For the tests reported here, static pressure measurements only are relevant. These were indicated on a precision Bourdon test gauge, range 0 - 70 bar, calibrated against a deadweight tester.

Two windows (Fig. 1c) (*6*), 25.4 mm diameter, for horizontal viewing, were located in opposite walls of the nozzle such that their axes and that of the instrument sub-assembly were all co-planar. The windows were made of toughened borosilicate glass, and were suitable for maximum conditions of 70 bar, and 450°C. The internal faces of the windows acted as flow boundaries and were traversed by the profile-piece. It was necessary therefore that for all operating conditions the windows should remain co-planar with the nozzle walls, and the window packings (*15*) were designed accordingly. A second glass disc (*7*) was provided within each window sub-assembly to secure, between disc and borosilicate window, a steam leakage space (*16*) which could be continuously drained. To provide additional protection for direct viewing, two separate pedestal guards were bolted to the laboratory floor, one for use with each window. Each guard was itself fitted with a small, shuttered window made of non-shatter glass.

3. Supporting plant

The supporting plant (shown diagrammatically in Fig. 2) was extensive, and a brief description only is given here. Steam was raised in a Stone-Platt oil-fired once-through boiler (*1*) at a maximum rating of 2900 kg/h at 76 bar gauge, 292°C from feed water (*2*) at 65°C. The steam was delivered approximately 0.99 dry to an oil-fired superheater (*3*)

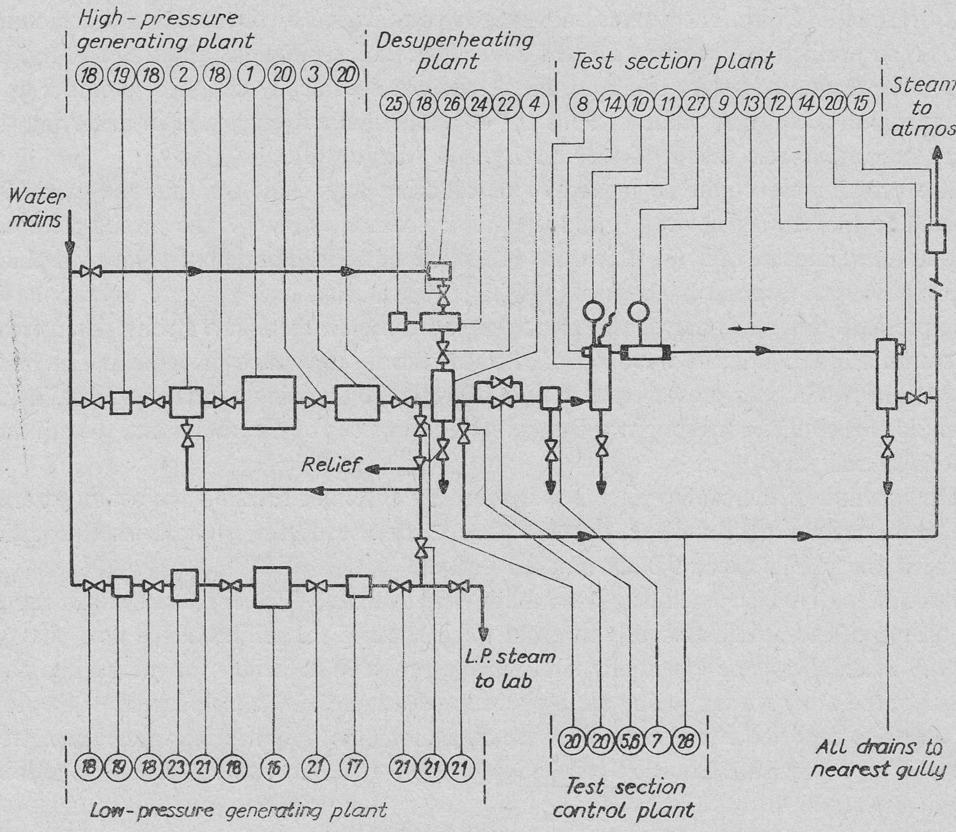

Fig. 2. Diagrammatic arrangement of the supporting plant
1 – high pressure boiler, *2* – boiler feedwater tank, *3* – high pressure superheater, *4* – high pressure desuperheater, *5* – large control valve, *6* – small control valve, *7* – strainer, *8* – steam reception reservoir, *9* – nozzle assembly, *10* – test pressure gauge, *11* – voltmeter connection, *12* – exhaust reservoir, *13* – nozzle exhaust pipe, *14* – reservoir windows, *15* – exhaust muffler, *16* – low pressure boiler, *17* – low pressure superheater, *18* – low pressure water valves, *19* – water treatment plant, *20* – high pressure steam valves. *21* – low pressure steam valves, *22* – high pressure water valve, *23* – feedwater tank, *24* – desuperheater pump, *25* – pump motor, *26* – desuperheater water tank, *27* – nozzle pressure gauge, *28* – nozzle by-pass pipeline

with a maximum rating of 2800 kg/h, 72 bar gauge, 350°C. The steam then traversed a water-injection desuperheater section, which was not employed for these tests; through large- and small-bore control valves (*5*, *6*) in parallel, and through a strainer (*7*) into the steam reception reservoir (*8*). The strainer was designed to remove all particles greater than 0.025 mm diameter, and was essential for reliable performance of the nozzle assembly (*9*) traverse mechanism. The steam reception reservoir was a vertical cylindrical vessel, 203 mm bore and 915 mm height. The stagnation pressure p_0 was indicated on a Bourdon test pressure gauge (*10*), and the temperature T_0, on a digital voltmeter (*11*). The exhaust reservoir (*12*) was of similar construction to the reception reservoir, but separated from it a distance of 4.6 m. This gap (*13*) was designed to admit, at a later date, if required, a long nozzle suitable for a very small value of $\dot{P}$. A shuttered window (*14*) was provided in each reservoir, optically in line with any interconnecting channel, to permit the passage of a light beam. The available mains water supply was not adequate for a condensing cycle, and the exhaust steam was released to the atmosphere through an elevated muffler (*15*) mounted on an adjacent chimney stack.

To attain the required steam output the boiler feed water (*2*) needed pre-heating. This was accomplished by raising steam in an adjacent low-pressure boiler and superheater (*16*, *17*) and blowing it into the lagged feed water tank (*2*). This tank was capable of storing 9100 kg of water, sufficient for 2.5 hours of high-pressure plant operation.

4. Nozzle commissioning problems

It was originally hoped to seal the nozzle block faces in metal/metal contact by heavy tightening of the nozzle bolts. This proved impossible, and leakage was liable to occur where three surfaces met such as at the nozzle ends and at the base of the instrument sub-assembly. Satisfactory sealing was eventually accomplished after applying several coats of liquid jointing compound to each face, allowing each coat to dry before applying the next coat.

The elevated working temperatures precluded the internal use of lubricants for the rack and pinion and sliding ports with the consequence that the traversing gear tended to seize when in use. The following procedure was adopted. All sliding parts were manufactured initially to a tight working fit at ambient temperature. Low-pressure steam was passed through the assembled nozzle, and the steam pressure was raised unitl, due to differential expansion, the traverse handwheel could no longer be turned. The rig was then closed down and dismantled, and surfaces which betrayed signs of rubbing were eased. This process was repeated with increasing pressures and temperatures until maximum working conditions were compatible with traversing the profile-piece using considerable handwheel effort. With such fitting, traverse was easier at lower conditions but the profile-piece clearances remained sufficiently small to minimise side leakage. There was no evidence from any of the pressure observations that such leakage had significantly influenced the flow characteristics through the nozzle.

Some trouble was experienced with flaking and cracking of the windows, and for the tests not requiring optical observations, cylindrical metal blanks were substituted. Windows were found to have an acceptable life for low-pressure operation, but a seriously reduced life as the pressure increased. In high-pressure operation, the windows were also observed to lose their transparency after an hour or two by abrasion of the steam-swept surfaces. This was believed to be due to scouring by fine particles contained in the steam, which were too small for separation by the strainer.

5. Experimental procedure

5.1. Higher pressure experiments (56 bar$>p_0>$10 bar)

Each higher pressure run occupied a working day. The low-pressure boiler and superheater were operated for about 0.75 h for feed water preheating only, and for the following 1.5 h for preheating simultaneously the feed water and the nozzle assembly with its associated plant. *The low-pressure equipment was then closed down.*

The high-pressure boiler and superheater were fired, steam was admitted to the apparatus, and the desired experimental conditions were attained after about 0.5 hr. Approximately 1.5 h remained for conducting experiments.

A static pressure search was conducted by traversing the profile-piece in the direction of the flow, i.e. from nozzle outlet to inlet. The search embraced 52 sets of readings, each set comprising the nozzle traverse handwheel setting, (which gave, on interpretation, the ratio l/L) the local static pressure p, and the reservoir pressure and temperature, p_0 and T_0. During the search, the reservoir temperature fluctuated $\pm 11°C$ due to cycling of the superheater, and readings were restricted to the time when the temperature was within $\pm 2°C$ of the nominal value. The reservoir pressure was maintained within $\pm 3\%$ of the nominal value by adjustment of the control valves. As a consequence of the fluctuations of the reservoir conditions, only about 30 per cent of the 1.5 h experimental period was productive, and only a single search was completed during the day-long run.

A total of thirty such searches were conducted, each search being analysed before performing the next search. In this way, the test programme was arranged so as to avoid gaps in the sequence of Wilson points defining the uncorrected Wilson Line (see Section 7, Analysis of results).

5.2. Lower pressure experiments (10 bar $>p_0>$ 7 bar)

The lower pressure searches embraced 52 sets of readings as in the higher pressure tests. However, as they involved using only the low-pressure boiler and superheater, they were easier to perform. It was therefore possible to conduct several searches during a day-long run, and a total of twenty such searches were completed during six day-long runs.

6. Arrangement of results

Of the 50 static pressure searches conducted [5], 4 were rejected because their reliability could not be accepted with confidence. The remaining 46 consisted of seven 'families' of searches, each family pertaining to a nominal stagnation pressure p_0. The seven families consisted of:

a) the higher pressure tests of: 7 at nominal p_0 of 55 bar gauge, 3 at 45 bar gauge, 5 at 35 bar gauge, 7 at 21 bar gauge, and 4 at 15 bar gauge;

b) the lower pressure tests of: 9 at nominal p_0 of 9 bar gauge, and 11 at 6 bar gauge.

The location of nucleation is betrayed by a deviation in static pressure from the value appropriate to an expansion which remains dry. Hence, it was necessary to perform a search within each of the seven families of tests which would constitute the 'nominal dry' search, i.e. one in which the initial superheat was sufficiently high for nucleation to be delayed, if it occurred at all, until late in the nozzle expansion. Hence, of the 46 useful searches, 7 were the 'dry' searches, and 39 resulted in spontaneous condensation within the nozzle, i.e. were 'wet' searches. The latter, upon analysis, yielded 39 Wilson points. The analysis is briefly described below.

7. Analysis of results

The 52 sets of readings comprising each search were plotted in a non-dimensional form, viz. the local pressure ratio p/p_0 against the local fractional nozzle length l/L. Several tests of a family including its dry search were plotted on the same sheet of graph paper. Fig. 3 shows (to a reduced scale) a representative case of the comparison of one wet search and the corresponding dry search for a nominal p_0 value of 35 bar gauge. The profile of the profile-piece is also included in this figure. Fig. 4 is an enlarged region of Fig. 3 in which divergence of these searches occurred.

Identifying the Wilson point (i.e. the point of maximum supersaturation ratio) from inspection of the pressure searches (Fig. 4) proved to be somewhat arbitrary. Most wet

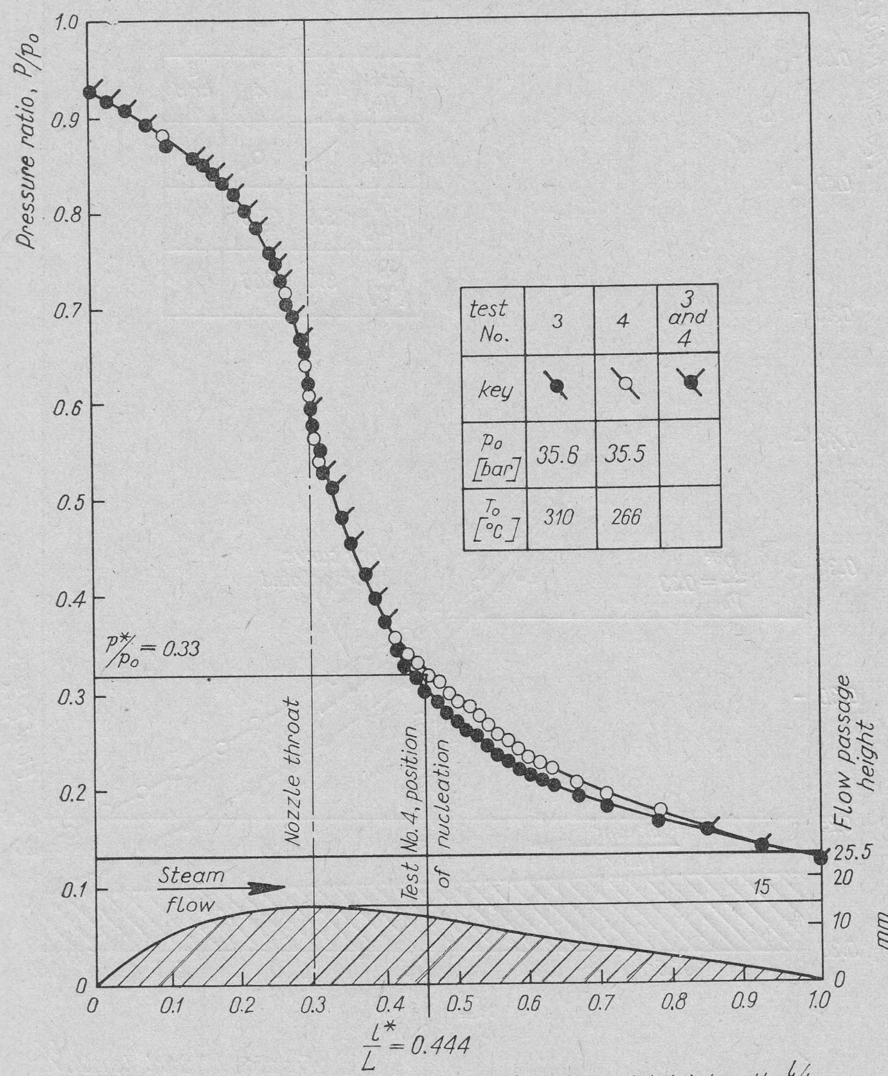

Fig. 3. Typical comparative search curves

searches deviated only slightly from their comparable dry curve, and a small distance downstream from the first deviation, a 'knee' in the curve was detected. None of the 39 wet searches exhibited an increase in static pressure that is usual at nucleation with low-pressure curves.

In the present experiments, the beginning of the 'knee' of each wet curve was presumed to indicate the onset of the decline in the supersaturation, and this location was assumed to correspond to the Wilson point.

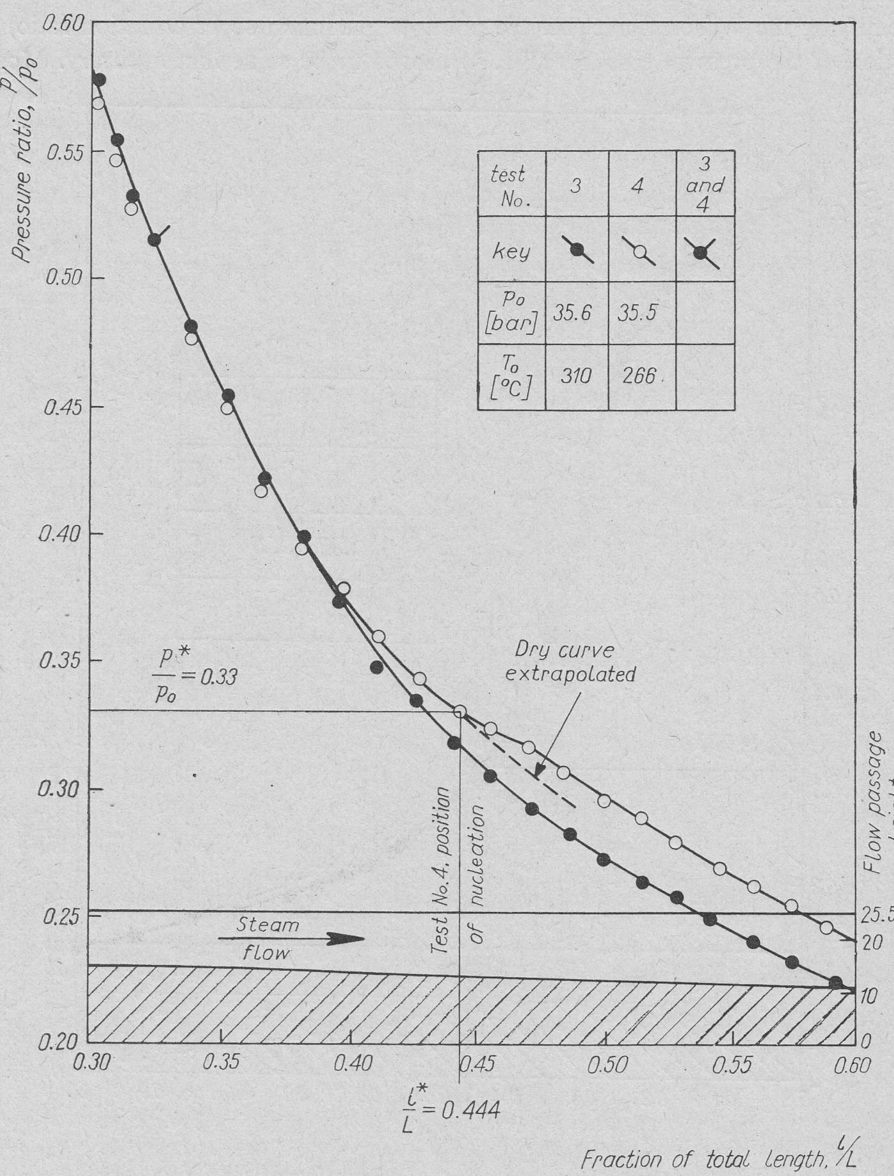

Fig. 4. Enlarged view of departure region of Fig. 3

After measuring the reservoir pressure and temperature, p_0, T_0, and deducing a value of Wilson point pressure p^* from analysis of the pressure searches, each nozzle expansion state-line was plotted on the *h-s* chart, assuming a nozzle isentropic efficiency (static/static basis) of 100 per cent. The *h-s* chart had been modified to include pressure and temperature variations extended into the supersaturated regions as published by Stodola [6] and Smith [7].

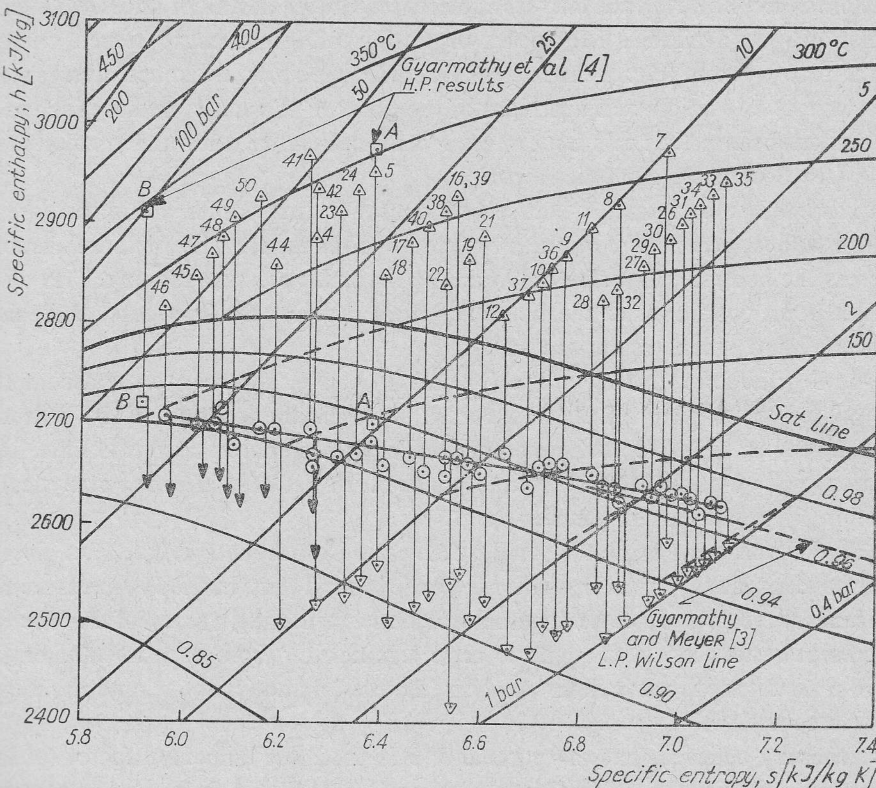

Fig. 5. Enthalpy-entropy chart showing the 39 expansion lines and the resulting uncorrected Wilson Line

In this way, 39 Wilson points were defined on the *h-s* chart, and a Wilson Line, corresponding to a $\dot{P}$ value of $10^4\ s^{-1}$, was constructed (Fig. 5). The two high-presure Wilson points (*A* and *B*) published by Gyarmathy *et al.* [4] and the overlapping section of the low-pressure line for $\dot{P}=10^4\ s^{-1}$ established by Gyarmathy and Meyer, are also shown in Fig. 5.

8. Discussion of the results

a. The gradual nature of the separation of the wet and dry search curves in high-pressure self-condensation with no increase in static pressure suggests that the process is less localised than at low pressures. This view is supported by Deich *et al.* [8] who obtained similarly shaped high-pressure searches (but without exhibiting knees) as also did Gyarmathy *et al.* [4].

b. The identification of the Wilson point in terms of a characteristic location on a wet pressure search curve (both for high and low pressures) presents difficulties. Gyarmathy [9] and Barschdorff [10] claim that, for high-pressure searches, the point of divergence of the wet and dry curves should be so defined, and that this view is supported by optical observation. Since, however, the curves in reference [4] were devoid of knees, no alternative interpretation was available. Moreover, inspection of low-pressure search curves due to several past workers (e.g. Binnie and Green [11]) show a distinct divergence from the dry curve at a location well upstream of the onset of the static pressure increase. The present writers believe that this issue must remain sub-judice until analytical studies are available (see Section 9; Analytical work).

c. It has been pointed out [3] that self-condensation first occurs within the core of the steam flow and appears later at the nozzle wall boundaries. The pressure disturbance has to cross the boundary layer before attaining the static pressure tapping. This displaces the Wilson point conditions at the boundary from those at the flow core, and this must be borne in mind when results are analysed.

d. Due to the factors mentioned in (b) and (c) above, and due to the assumption in the analysis of isentropicity of the flow for all searches, the location of the Wilson Line (Fig. 5) can only be regarded, at the present time, as provisional. A corrected Line, finalised for location, will be published in a second paper on this subject after the analytical work (see Section 9) has been completed.

The 39 Wilson points exhibit a standard deviation of about 7 kJ/kg. This gives some cause for concern, as Gyarmathy and Meyer [3] found that, in the low-pressure region, Wilson Lines were located close together for widely differing values of $\dot{P}$. The scatter in the present results is not thought to arise significantly from experimental error, but rather from assumptions made in the analysis (factors (b) and (c) above, and the isentropic efficiency assumption).

It is generally believed that the parameter $\dot{P}$ is the most influential factor (at least at low-pressure) in placing the Wilson Line. It is, however, not the only one, and a contribution to the present scatter of Wilson points probably arises also from factors not yet identified [12, 13].

e. Binnie [14] drew attention to the existence of standing (i.e. non-propagating) waves within a Laval nozzle passing low-pressure steam in steady-flow. He attributed such waves to two-dimensional flow effects. Similar waves were observed by the authors during the lower pressure searches, but not during the higher pressure searches.

f. A few optical observations were made by viewing the flow through one nozzle window against the illuminated background of the other window. The flow appeared completely transparent for expansions accompanied by self-nucleation, up to pressures p_0 of 21 bar gauge approximately. Further pressure increase, up to a maximum of 55 bar gauge, progressively facilitated observation of a fog. At the lower values within this range, the fog had a tenuous red/yellow tint, becoming darker towards the nozzle exit. As p_0 increased, the fog darkened more rapidly through a deep brick red to a dark tea colour streaked with black. These observations confirm those reported by Gyarmathy *et al.* [4], although, unlike those workers' observations, no sharp transition from transparent to opaque flow conditions was seen at self-nucleation.

These optical observations indicate that high-pressure self-condensation fog droplets grow considerably faster than those formed within low-pressure flows.

9. Analytical work

In supersaturated steam, the only function of state susceptible to reliable measurement is the static pressure and this limitation has been a serious impediment to all investigations (both at low and high pressures) concerned to locate a Wilson Line. The Wilson Line presented in Fig. 5 is based on static pressure measurements and requires correction. Such work is in hand with the collaboration of Dr. F. Bakhtar *et al.*, Department of Mechanical Engineering, University of Birmingham. Briefly, the corrections to be made are as follows. A computer programme has been prepared combining the state, flow and nucleation equations for a step-by-step analysis of the high-pressure expansion process. The nozzle friction factor f for a given location is included as a variable. The dry search curves presented here are known to be accurate, and it is possible to align them with the corresponding theoretical curves by manipulation of the values of f. The theoretical curves then indicate the temperature at which nucleation occurs, and this provides a second function of state for location of the Wilson point on the h-s chart.

Preliminary results indicate that the corrected Wilson Line will lie near $x=0.975$ at about 2 bar, declining slowly to approximately $x=0.970$ at 28 bar.

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Spontaniczna kondensacja w parze wodnej ekspandującej pod dużym ciśnieniem

Streszczenie

Wykonano dyszę de Lavala przeznaczoną dla ekspandowania pary wodnej ze stosunkiem ciśnień około 7 : 1 przy następujących parametrach spiętrzenia: maksymalne ciśnienie 70 bar, maksymalna temperatura 320°C. Dysza miała prostokątny przekrój poprzeczny. Umieszczony w niej element ruchomy zapewniał stałą szybkość ekspansji $\dot{P}=-(1/p)\,(dp/dt)$ równą $10^4\ s^{-1}$ w obszarze przepływu naddźwiękowego (kondensującego). W górnej ściance dyszy umieszczono nieruchomą sondę do pomiarów ciśnienia statycznego. Okienka ze szkła boro-krzemowego umieszczone w ściankach umożliwiały obserwowanie przepływu w tym miejscu.

Przedstawiono prowizoryczną linię Wilsona, otrzymaną przy założeniu ekspansji izentropowej, z 39 punktami doświadczalnymi. Linia ta jest prawie prosta, jej współrzędne: $p=34{,}5$ bar, $x=0{,}944$; $p=1{,}38$ bar, $x=0{,}970$.

W artykule opisano dyszę i związane z nią stoisko oraz omówiono problemy dotyczące uruchamiania aparatury oraz otrzymywania wyników doświadczalnych i ich analizy. Analiza ta jest prowadzona we współpracy z Uniwersytetem w Birmingham. Skorygowana linia Wilsona o ostatecznie ustalonym położeniu zostanie podana w następnej publikacji na ten temat.

Спонтанная конденсация в водяном паре, расширяющемся при высоком давлении

Резюме

Выполнено сопло Лаваля, предназначенное для расширения водяного пара при отношении давлений ок. 7 : 1 и при следующих параметрах торможения: максимальное давление 70 бар, максимальная температура 320°C. Форма поперечного сечения сопла — прямоугольная. В сопле помещен подвижной элемент, обеспечивающий постоянную скорость расширения пара $\dot{P}(=-(1/p)(dp/dt))$ порядка 10^4 $сек^{-1}$ в диапазоне сверхзвукового (конденсирующегося) течения. В верхней стенке спола помещен неподвижной зонд для замеров статического давления. Смотровые бор-кремниевые стекла, размещенные в стенках, позволяют наблюдать течение в данном месте.

Представлена предварительная линия Вильсона, полученная при предположении изентропного расширения с 39-тью экспериментальными точками. Эта линия является почти прямой, характеризующейся следующими координатами: $p=34{,}5$ бар, $x=0{,}944$; $p=1{,}38$ бар, $x=0{,}970$.

В статье описывается сопло и связанный с ним стенд, а также обсуждаются проблемы, касающиеся ввода аппаратуры в действие, получения экспериментальных результатов и их анализа. Этот анализ проводится в дальнейшем в сотрудничестве с университетом в Бирмингам. Исправленная линия Вильсона с ее окончательным расположением будет публиковаться позднее.