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III НАУЧНАЯ КОНФЕРЕНЦИЯ

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DAVID H. EVANS*, WALTER D. POUCHOT**, GERALD J. BARNA***

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Wet Vapor Turbine Flow Study

Introduction

In wet vapor turbines, such as those used in central station steam power plants and advanced space power systems [1], the moisture which forms and collects on blade and casing surfaces reduces turbine efficiency and can cause serious damage to turbine blades and shrouds. The NASA, over the past decade, has undertaken programs investigating the flow phenomenon in wet vapor turbines as part of its interest in Rankine-cycle power plants for space. Both analytical and experimental programs have been undertaken [2] and [3], as well as the testing of two-, three stage potassium turbines [4, 5, 6, 7], as part of its work on technology for advanced Rankine-cycle power plants. With the increasing application of central station nuclear power plants and the higher moisture levels in the steam turbines, there has been likewise a high level of interest in these phenomenon by Westinghouse Electric Corporation. The work described in this paper was performed by Westinghouse under NASA contract.

This experimental program was aimed at improving our understanding of the moisture flow in wet-vapor turbines. A multistage steam turbine was used as the test vehicle. Objectives of the program were threefold: (1) visualization of the moisture flow in the turbine through high speed photography and visual observations; (2) measurement of the effectiveness of rotor casing slot and stator trailing edge slot moisture removal devices; and (3) measurement of the effects of the moisture on turbine efficiency.

1. Condensate flow phenomena

In steam or alkali metal vapor turbines the bulk of the moisture is present as a fine fog in the bulk flow. In high purity systems the primary mechanism of condensation is spontaneous nucleation in the bulk vapor. In less pure systems fine particles can be important nucleation sites.

* Steam Turbine Division, Westinghouse Electric Corporation, Philadelphia.
** Astronuclear Laboratory, Spelling Electric Corporation, Pittsburgh.
*** National Aeronautics and Space Administration, Lewis Research Center, Cleveland.

A widely held model of the qualitative aspects of condensate flow in wet vapor turbines is given in NASA CR-1830 [2]. The following discussion is mainly along these lines.

If a superheated vapor expands in a nozzle or turbine until the temperature of the vapor is reduced to that of equilibrium saturation, the vapor does not condense in any appreciable quantity immediately. Rather the vapor must be cooled to produce sufficient supersaturation to cause rapid condensation. The condition at initiation of rapid spontaneous condensation is called the Wilson point or line. At the Wilson line, condensation takes place rapidly and the moisture content quickly approaches equilibrium. Thereafter, the expansion process follows with but slight lag an equilibrium expansion because the original spontaneous nucleation creates sufficient surface area to allow further condensation to occur with minimal supersaturation.

As originally formed, the condensation nuclei are extremely small and are of relatively uniform size because of the short period of time involved. The nuclei grow quite rapidly to about 0.2 micron diameter as the supersaturation potential created by the expansion in advance of spontaneous condensation is exhausted. Thereafter, a slower growth takes place as the droplets progress through the turbine. The calculated supersaturation in equivalent moisture to initiate spontaneous condensation in steam turbines is about 2.5%.

Because of their small size, most of the condensate particles remain in the vapor flow. Only a small percentage of the condensate fog collects on surfaces. It is often hypothesized that the major mechanism in collection of these particles is by inertial impaction on the nose and concave surface of the turbine blades. The estimated values of moisture collection for this test turbine are based on this assumption.

The small percentage of fog particles collected form rivulets, films, and drops on the blading surfaces. On the rotating blading, the predominant force is that of the centrifugal field of the blades. Under this force, the liquid collected on the rotors flows nearly radially outwards and is thrown from the tips of the blades. Because of the high peripheral velocity of the rotor blades and shrouds, the liquid flung from them is very well atomized and rarely causes any erosion damage of consequence to either the turbine casing or a succeeding row of stator blades. The liquid flung from the rotors mostly collects on the turbine casing. It runs along this casing towards the turbine exit, if not removed, under the drag of the vapor.

According to the model, on the stator blades the primary force acting on the collected liquid is the drag force of the mainstream flow. Under this force, the liquid flows to the rear of the stator where it collects until torn from the stator as rather large particles. This implies that the collected liquid follows the bulk flow streamlines and on a time average basis is uniformly distributed from hub to tip of the stators.

According to the model, liquid is torn from the back edges of the stator vanes as relatively large globs. These globs undergo a breakup process into small drops in the wake just downstream of the stators. These smaller drops accelerate rapidly in the space between stator and rotor. However, in the space available between stator and rotor, the drops do not attain vapor stream velocity and because of the velocity vector difference, can strike the nose and convex surfaces of the rotating blades with rather large normal velocity components. In turbines with high tip velocities some of the larger drops strike with sufficient force to produce erosion of the blade leading edges, particularly at the rotor blade tips.

Moisture predictions

Prior to the design of the test hardware, calculations were made to predict the moisture conditions at the fourth stage observation points using available theory. The purpose of the calculations was twofold: to provide design criteria for the test hardware and to provide information for a comparison between a theoretical analysis and actual observations.

Fog particle radii

Estimates of fog particle radii were made using empirical data from Gyarmathy and Meyer [8]. This information, for wet steam flow in nozzles, was used to estimate the average particle radius at the Wilson condensation point. The fog particle radii at downstream locations were then estimated assuming uniform droplet growth with allowance for moisture lost by collection on turbine surfaces.

Numbers were generated for a turbine inlet pressure of 2.28 Bar. The design quality of the steam exiting the fourth stage of the turbine is 90%. Fog particle size estimates for various locations in the fourth stage are given below:

Fourth stage location	Average fog particle radius (microns)
Stage Inlet	0.19
Stator Exit	0.20
Stage Outlet	0.21

Amounts of moisture collected

The estimates of the fog particle radii were used to calculate the fraction of condensed moisture collected using a procedure after Fentress [2]. Previous calculations by the Fentress procedure gave the results that most of the moisture is collected by the concave surfaces and very little collected on the leading edge of the turbine blades. Therefore, only concave surface collection was considered in preparing the estimates of collected moisture fractions at the fourth stage of the test turbine. The estimated collected moisture fractions are given below:

Fourth stage location	Cumulative collected fraction of total moisture-%
Stage Inlet	4.8
Stator Exit	7.0
Stage Outlet	10.0

The foregoing numbers indicate that only about 1% of the total turbine flow collects on the turbine surfaces even though 10% of the total flow condenses. Most of the condensate remains vapor-borne.

Atomized drops

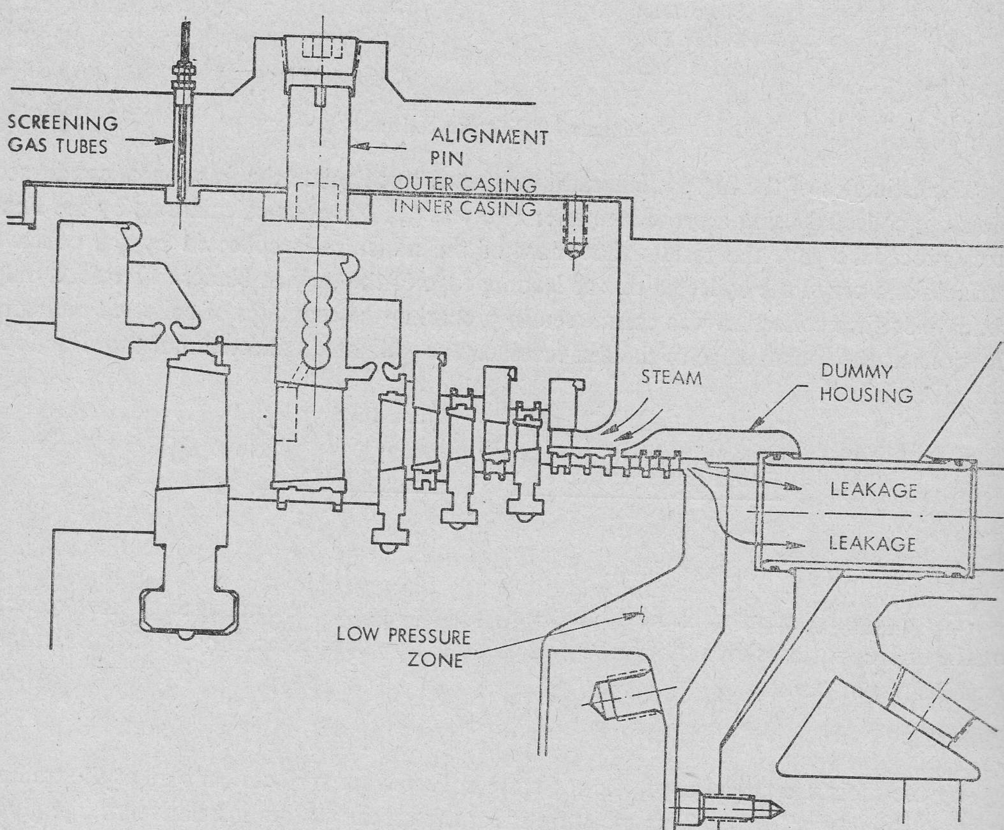
By the moisture model used, the moisture collected on surfaces ends up at the trailing edges of the stator blades. This moisture is torn from the stators in relatively large globs by the vapor flowing past. It is further atomized into small drops in the wake of the stator blades by a secondary process. These drops accelerate rapidly downstream of the stators. While the secondary atomized drops are small in absolute sense and accelerate rapidly, they are much larger than the fog particles and do not reach vapor velocity before they impact the leading edges of the rotor blades.

The atomized drop calculations were based on blade surface velocities established through the use of a computer code by Katsanis [9]. These surface velocities were then a part of the input to an atomized drop code [10]. The latter code calculates atomized drop diameters and drop velocities downstream of the stator blades.

The maximum secondary atomized drops from the fourth stators were calculated to be about 155 microns for the 2.28 Bar turbine inlet pressure condition. The distance downstream of the fourth stator at which secondary atomization is completed was calculated to be about 0.5 cm. The velocity of a 155 micron drop 1 cm downstream of the fourth stator was found to be about 13 m/sec and at the inlet plane of the fourth rotor blades about 66 m/sec.

2. Test turbine description

A simplified longitudinal section of the four-stage test turbine is shown in Fig. 1. All photographic testing was performed on the fourth turbine stage. Moisture removal slots



Big. 1. Wet vapor turbine longitudinal

are located in the casing at the trailing edge of the third and fourth stage rotor blade rows and in the trailing edge of the fourth stage stator blades. Shrouded rotor blades are used in all stages. A double-casing design is employed with the inner and outer casing separated by an annulus which is, essentially, at turbine inlet pressure.

The turbine has a constant mean diameter flow path of 64.2 cm with blade heights from 1.07 cm to 6.93 cm. The pitch of the fourth stage stator blading is approximately

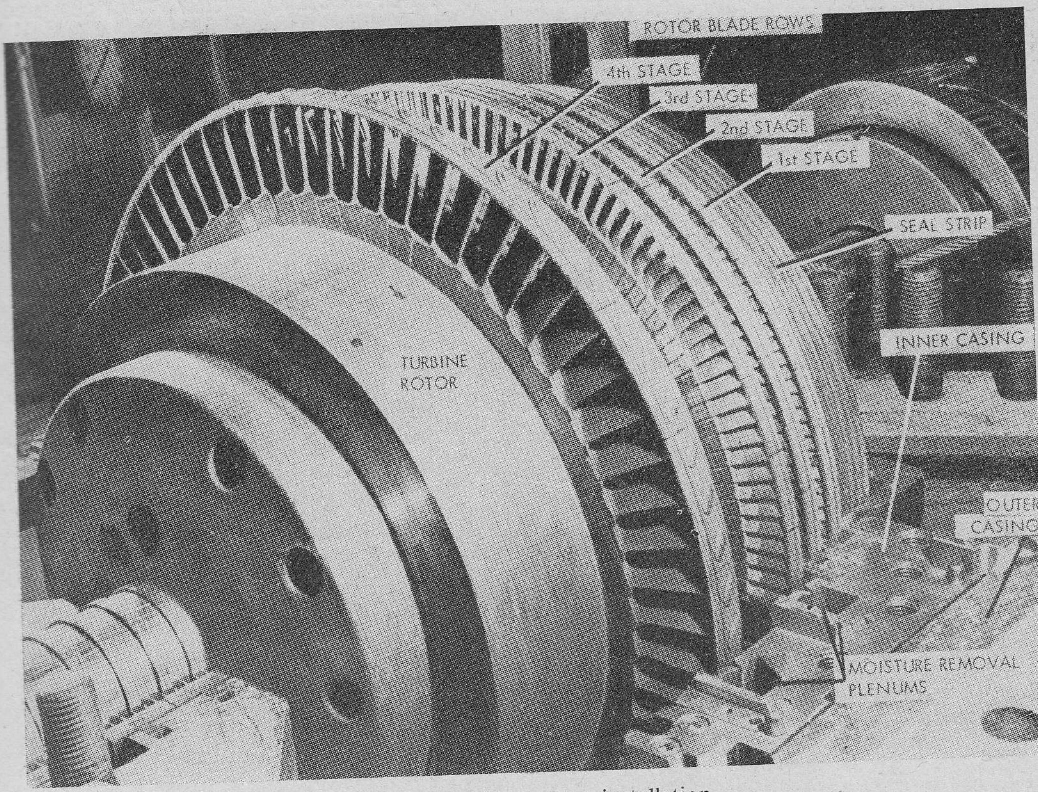


Fig. 2. Turbine rotor installation

4.07 cm at the three-quarter blade height position. A 2.54 cm axial spacing is used between the fourth stator and rotor blade rows to allow sufficient space for the insertion of the photographic instruments. A view of the turbine rotor assembled in the lower half of the inner casing is shown in Fig. 2; the view is looking toward the upstream end of the turbine. The fourth stage rotor blades and shrouds were painted with a flat black paint to improve visualization of the spray of droplets off these surfaces.

The fourth stage blades are shown in Fig. 3. There are four slots in the stator blade trailing edge to remove moisture. Each slot is approximately 0.025 cm wide and 0.63 cm long. The extracted moisture and vapor flow through the slots to a header internal within the blade and then through a riser hole to the plenum drilled in the blade root. An extraction flow annulus is formed upon assembly of the stator blade row. O-rings are used in the machined groove to seal the annulus.

Rigid borescopes and fiber optic light tubes were selected as the general photographic system design approach. Access holes were provided in the turbine for photographs of the moisture flow on the stator blade pressure and suction surfaces, at the trailing edge, in the stator blade wake, and at the exit of the last rotor blade.

Due to the double-wall construction of the turbine, special care was needed in the design of seals to prevent leakage around the borescopes and light tubes. Since the optical systems are relatively fragile compared to the turbine components, the sealing systems were designed

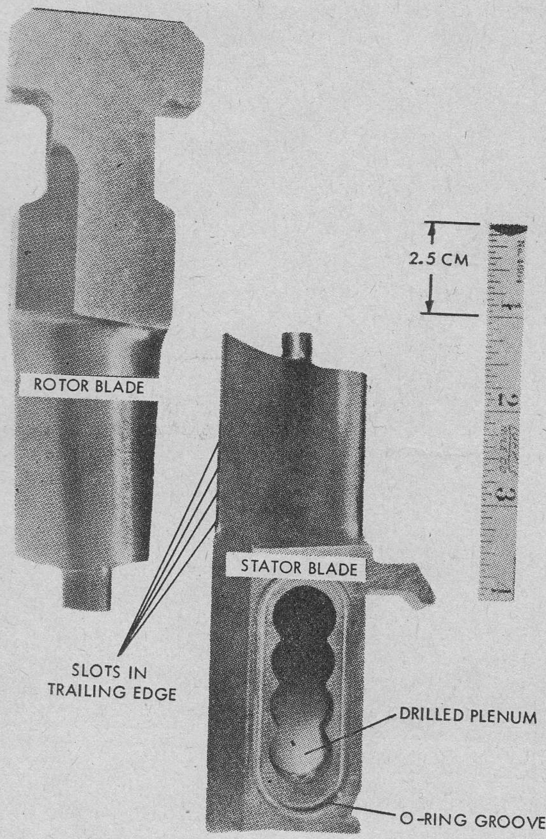


Fig. 3. Test stage blades

to move in a fixed plane. Figure 4 shows the sealing arrangement used for one borescope location. In this example a seal which is fixed in position is used at the outside of the inner casing. A "floating" seal is used at the outside of the outer casing. This seal is held in place radially by the seal retainer shown. O-rings are used to seal around the borescope and at the face of the "floating" seal. A clamp on the outside of the turbine seal assembly holds the borescope in place. Eleven seal assemblies similar to the one shown, were used in the turbine for the photographic instrumentation.

At three locations in the turbine, the borescopes were inserted on radial lines into the stator blade airfoil section. Since the blades were placed individually into the inner casing to form the blade row, careful procedures were required to insure proper hole alignment between the inserted blade, inner casing and outer casing.

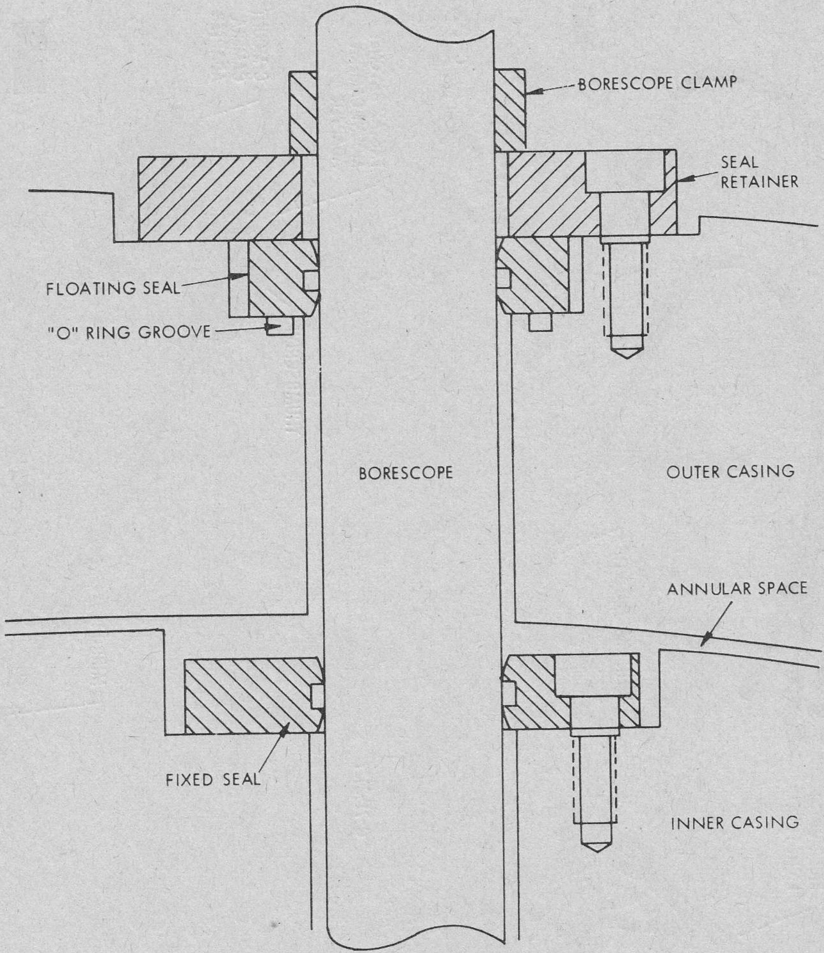


Fig. 4. Borescope sealing

3. Photographic equipment

An important consideration in the photographic system design was to avoid disturbing the flow being photographed with the photographic instrumentation. Tests were performed in a two-dimensional high Reynolds number air cascade using blading similar to that of the fourth stage stator. Results of these tests indicated that small diameter instrumentation could be placed in certain locations in the stator-rotor blade axial space without seriously disturbing the flow either on the surface or in the wake of the blade being photographed. These tests showed further that a large cutout in the adjacent stator blade could be tolerated without seriously affecting the flow on the blade being photographed. These criteria were used as guidelines in the placement of the optical instrumentation in the turbine.

Another important consideration in the photo system design results from the fact that the submicron diameter fog droplets scatter and attenuate the light. Therefore, to minimize

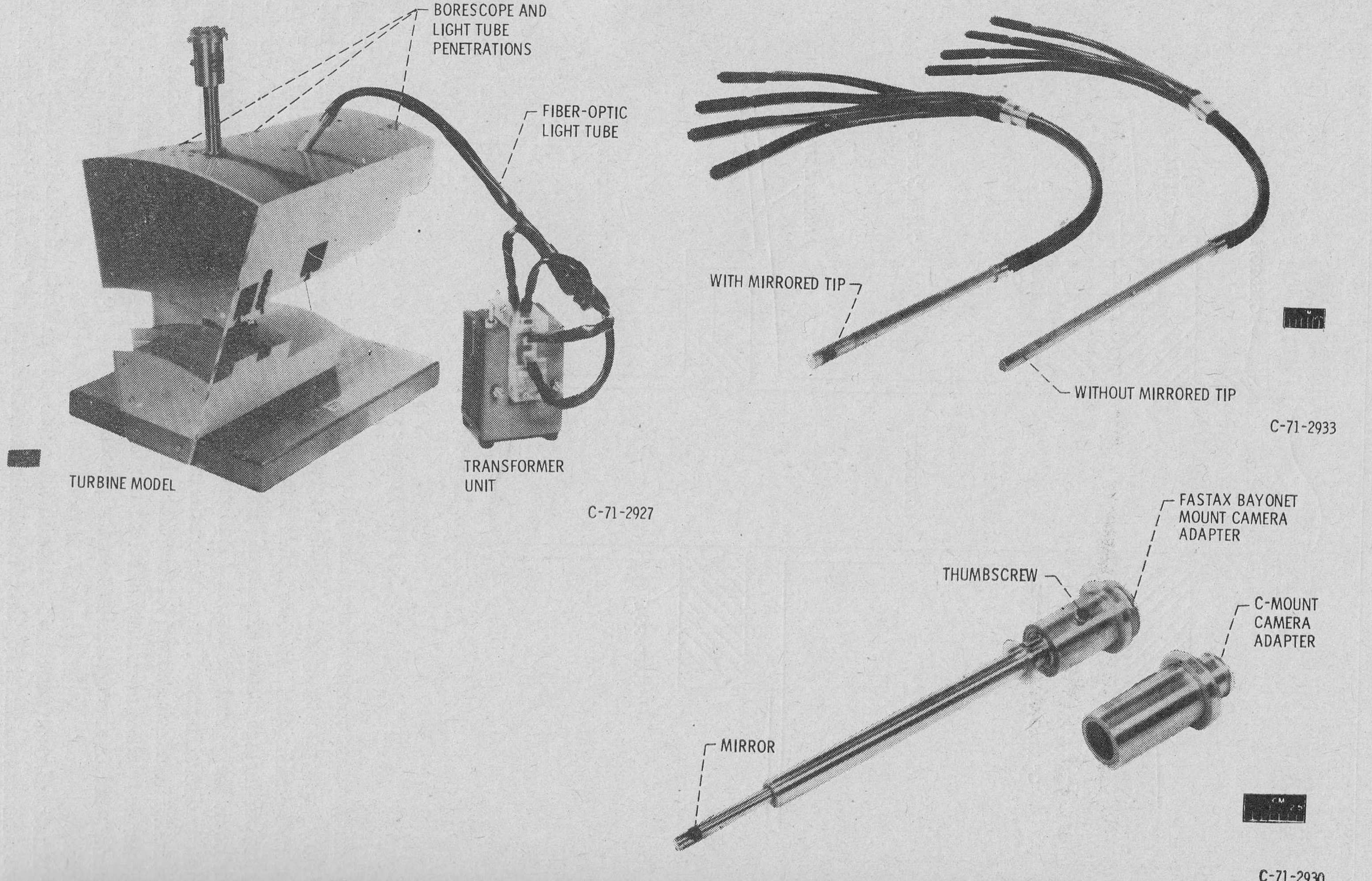


Fig. 5. Turbine model and photographic instrumentation

these effects the lighting to subject, and subject-to-borescope distances were kept as small as possible without significantly affecting the flow.

While most of the liquid in the turbine is in the form of submicron diameter fog droplets, the small percentage that is collected by blade and casing surface can run over the borescope mirrors and obscure the view. To keep the borescope mirrors free from liquid there was, at each borescope location in the turbine, a small hole or tube to direct a jet of "screening" gas over the borescope mirror.

Photographic checkout tests in a simple model of the turbine fourth stage using air-sprayed water to simulate moisture flow verified that good results could be obtained for all views with the photographic system designed. Shown in Fig. 5 is the turbine model and some of the photographic equipment including a borescope, fiber optic light tube and the transformer unit which holds the flashtube for the high speed stroboscopic lighting system. The 1.43 cm diameter light tube consists of a rigid stainless steel-clad portion which is inserted in the turbine, a flexible portion, and a quadrifurcated light gathering section with rigid rectangular ends. The ends are inserted into the transformer unit and held in close proximity to a Xenon flashtube. A high speed stroboscopic power source triggers the flash-tube. All high speed motion pictures were run at 3000 frames/second. The borescope is 0.953 cm over the portion which is inserted into the flow path and 1.91 cm elsewhere. The tip portion contains a fixed mirror. The borescope magnification is $X\,0.2$. A more detailed description of the photographic system development and the optical equipment is given in NASA TM X-2763 [11].

Figure 6 is a photograph of the fourth stage stator blade row. The penetrations for

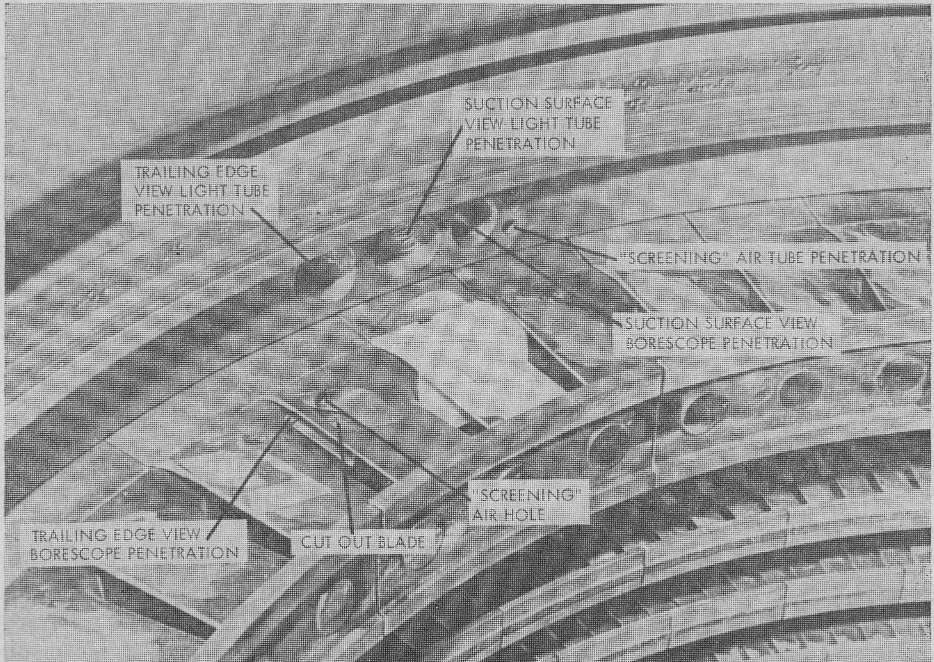


Fig. 6. Fourth stage stator blade row

photographing the blade suction surface and trailing edge are shown. The blade being photographed was painted white for the checkout tests to reduce the amount of illumination required for proper film exposure. A black grid helps orient the viewer.

In order to accommodate the penetrations of the borescopes, light tubes, screening gas lines and moisture extraction pipes, 79 holes were drilled into the inner and outer casings and some individual blades.

Of the 79 holes drilled only one was in error such that it affected the photographic results. The light tube penetration hole in the inner casing for the trailing edge view was drilled such that optimum lighting could not be achieved. As a result the lighting was less than

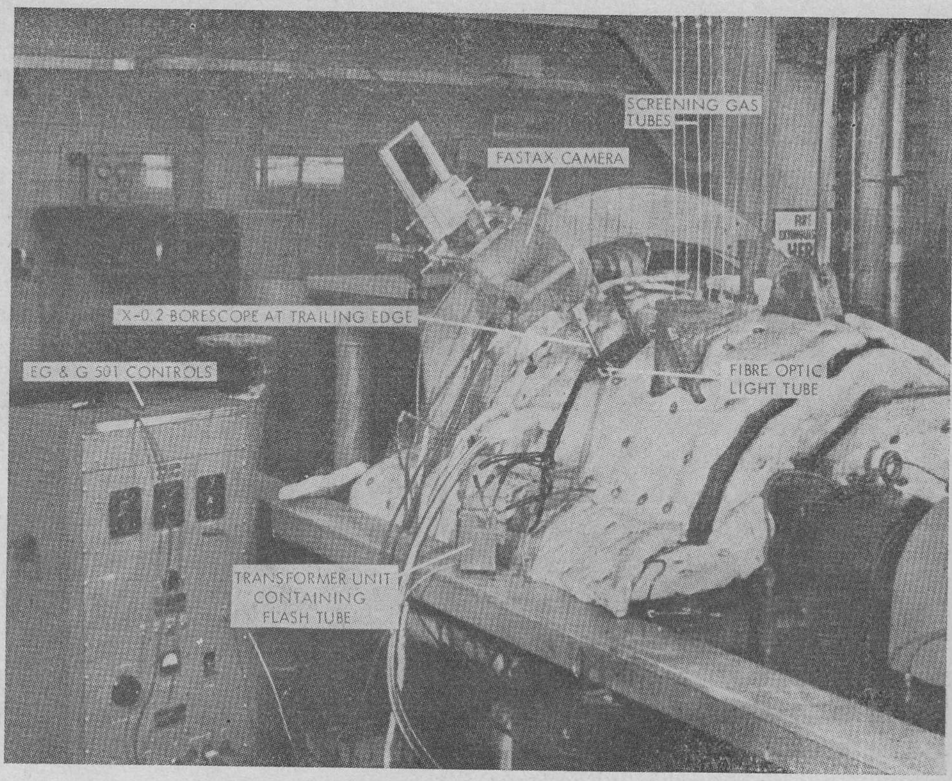


Fig. 7. Photographic equipment when testing

required for the photography of the fourth stator trailing edge slots. In order to ameliorate this situation one of the straight through light tubes was modified by cutting the end at an angle in order to deflect the light 22 degrees from the light tube axis. This was successful although only the two outermost slots were sufficiently illuminated.

The camera mounting system is shown in Fig. 7. The borescope and light tube in the trailing edge position can be seen along with the light source and the EG&G 501 high speed strobe control console. The mounting brackets provide motion in the axial direction, and in the radial direction for focusing.

As previously mentioned the photographed blades were painted white prior to the photo checkout tests but the paint deteriorated in a relatively short time. Therefore, prior to the actual photo tests all paint was removed and the blade surfaces restored as best possible to the original machined condition. Although some reduction in light intensity resulted, earlier photographic work had demonstrated that better contrast could be obtained with the normal blade finish. The last rotor blade row was painted black and the shroud white for orientation purposes when viewing the film. The rotor blade paint was retained throughout the test program and, although some paint was lost, it is believed based on results given in reference [11], that visualization was enhanced by painting the blades.

4. Moisture removal equipment

The performance of third and fourth rotor blade removal slots is dependent on proper sizing of the slot area, the removal plenum geometry, and the number of extraction pipes taking the moisture and vapor flow out to the rest of the collection system. A large number of small pipes is desirable for uniform removal. Due to the double wall construction of the test turbine and the number of penetrations required for the borescopes and light tubes the number of extraction pipes was limited.

For the fourth stage stator blade removal system, the slotted trailing edge was compartmentalized to reduce the effects of the radial pressure gradient at the stator exit. This gradient is approximately 0.0107 bar from the outer to the mean diameter for a stator exit

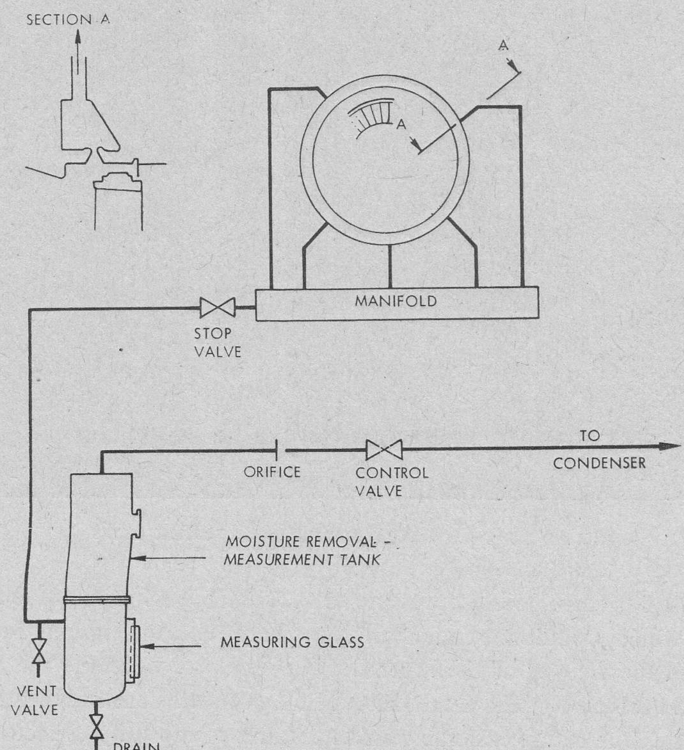


Fig. 8. Fourth stage rotor casing slot removal system

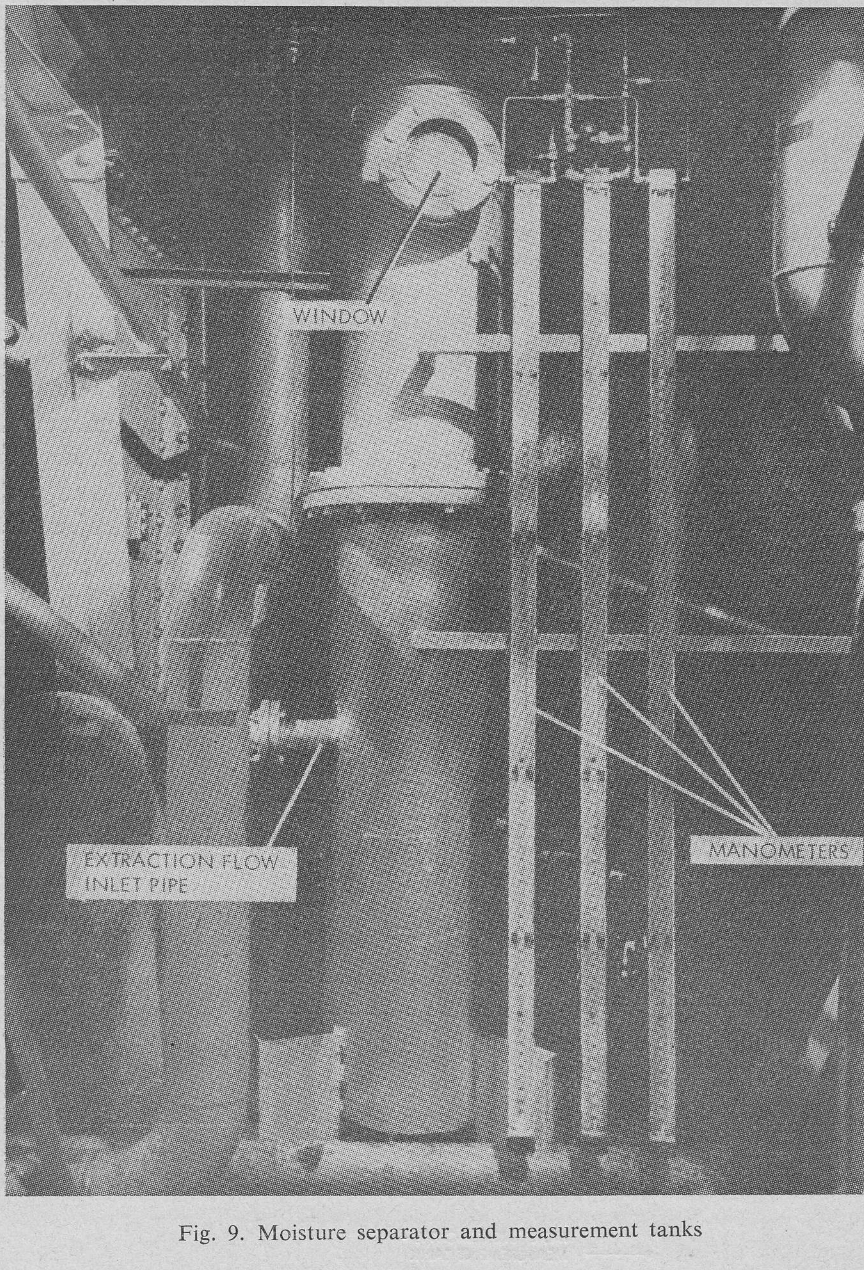


Fig. 9. Moisture separator and measurement tanks

pressure of 0.174 Bar (turbine inlet pressure of 2.28 Bar). This gradient tends to promote a radial inflow which would carry moisture into the slot in the tip region and out into the main flow in the vicinity of the inner slot. In order to overcome this, the extraction slot velocity head must be of the same order of magnitude as the radial pressure gradient at the slot mouth. Due to the extremely small amount of moisture collected by the stator blades, it is necessary to extract a quantity of steam along with the moisture to induce a sufficiently large velocity in the slot.

Two separate collection and measuring systems for the extracted moisture flow were provided: one for the rotor casing slot devices; and the other for the stator trailing edge device. A schematic diagram for the rotor casing slot moisture removal and measurement system is shown in Fig. 8. The schematic for the fourth stage stator slot removal and measurement system is similar. Individual pipes connect the moisture removal plenum in the turbine inner casing to the manifolds exterior to the turbine. Six pipes were used for the third stage and five for the fourth stage. Liquid flow rates were based on level change with time in calibrated tanks. The separation of condensate from the extracted flow is achieved by a wire mesh mounted near the top of the tank. The vapor flow rates after separation of the liquid were determined by sharp edged orifices mounted in the piping between the separator tank and the condenser. A flow control valve is used to change the amount of flow extracted from the turbine.

The rotor slot separator tank is shown in Fig. 9. The tank diameter of approximately 16 inches was influenced by the necessity of keeping the vapor velocity through the wire mesh sufficiently low to assure 100 percent liquid removal. The window near the top of the tank permits observation of the condensate in the mesh to confirm visually that moisture separation is effective.

5. Photographic observations

Six locations or types of photographic observations were planned for this test program. Four views produced worthwhile results. These are views of: (1) the fourth rotor blading

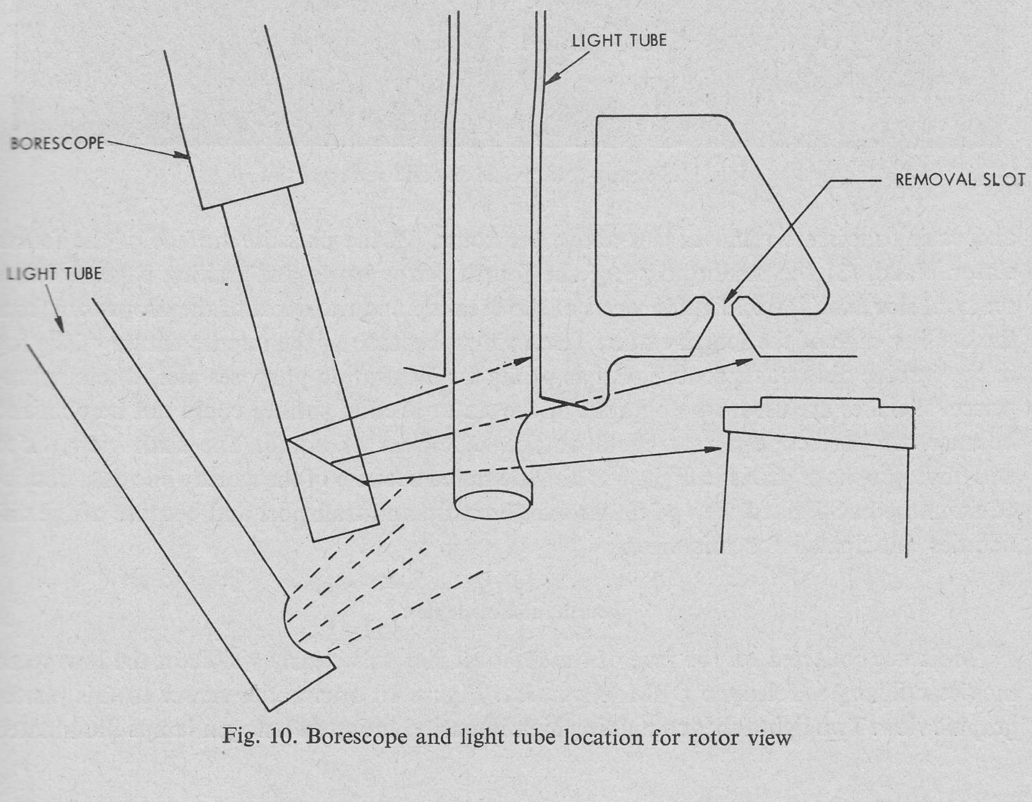
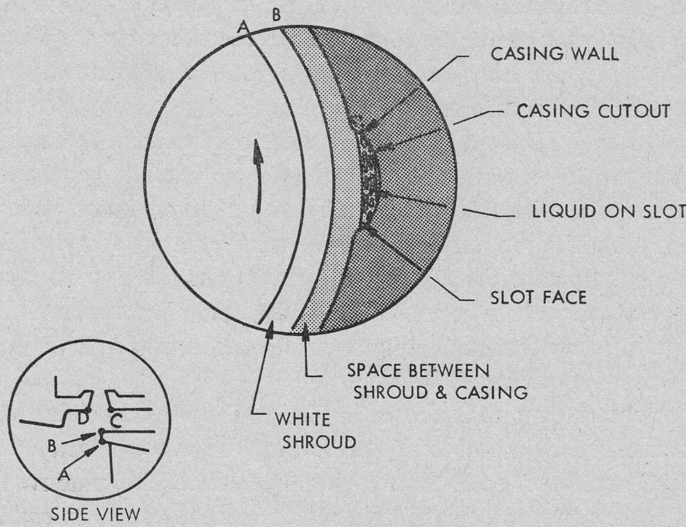


Fig. 10. Borescope and light tube location for rotor view



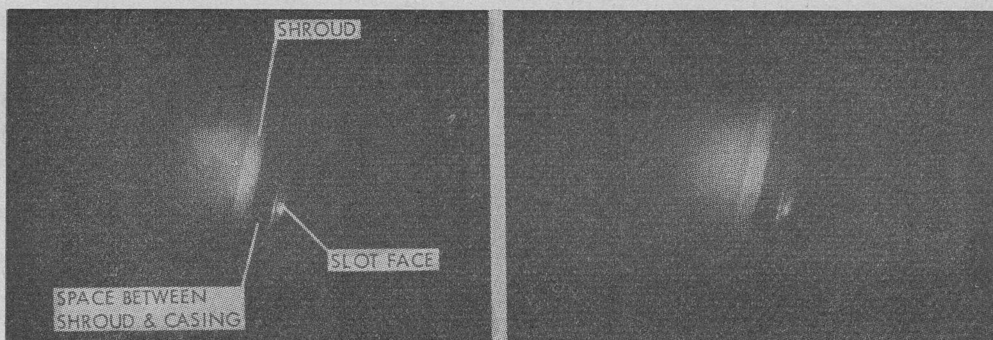


Fig. 11. Photos–rotor blade exit and remowal slot

and casing moisture removal slot above the rotor, (2) the pressure surface of the fourth stator blade, (3) the trailing edge of the fourth stator blade and trailing edge moisture removal slot and (4) backlighted views of the breakup and transport of the drops torn from the trailing edge of the fourth stator. These views, because of the intense nature of the fog in the turbine did not reproduce well as prints for illustration purposes and, where appropriate, sketches are used. Photographs of the stator suction surface could not be obtained because the borescope mirror could not be kept clear of liquid. The sixth view, 1.5× still photographs of drops in flight was not attempted because of the worthwhile data obtained from the backlighted view of the droplet breakup and transport and because of the difficulties anticipated for this view.

Fourth rotor blade view

Moisture collected on the face of the removal slot was clearly visible in the low speed movies utilizing a Teledyne DBM-44 camera. Figure 10 orients the viewer to this photographic view. Two light tubes containing high intensity, tungsten halogen lamps illuminated this view. The best camera speed was 60 frames/second. Referring to Fig. 11, motion of the liquid on the slot face was detectable as streams traveling in the tangential direction although no deductions could be made as to the velocity of the liquid. Very little change was observed in the quantity or motion of the liquid on the slot face when the removal slot was activated. There were no indications that the liquid was going into the annular collection chamber. The tangential motion of the liquid was in the same direction as the turbine rotor which, of course, is the direction of the drops being thrown off the fourth rotor blade shroud.

Considerable loss of quality occurs in the printing process although a fairly uniform distribution of fog over the entire viewing area can be seen. This is consistent with visual observations made when the camera was replaced with an eyepiece.

Pressure surface view

Figure 12 orients the viewer for the pressure surface view. A cover plate was attached to the blade containing the borescope and light tube to prevent steam flow through the cut-out blade. Very little moisture could be observed as seen on Fig. 13. The photo is of

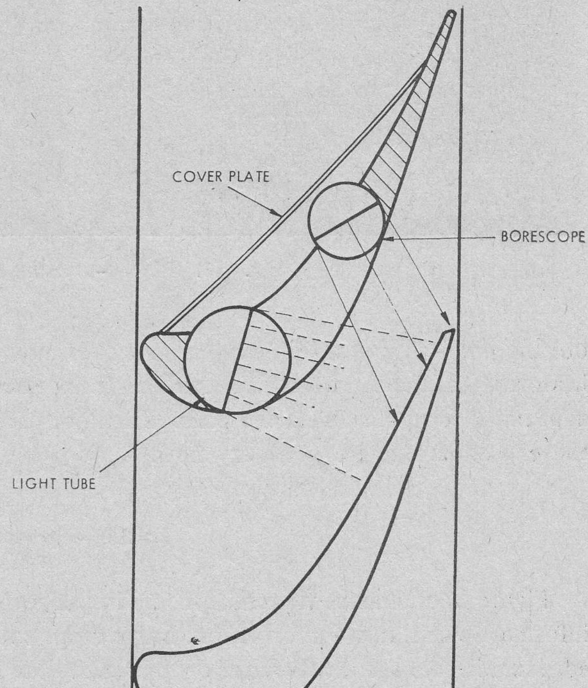
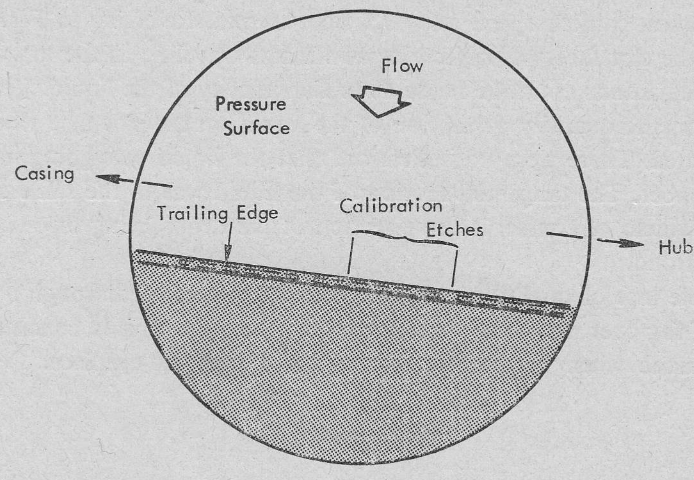


Fig. 12. Pressure surface view–schematic

sufficient quality to show machining marks and two calibration lines located 0.64 cm apart. A ribbon of water clinging to the trailing edge can clearly be seen in the film but this feature is lost in the photographic printing process. However, no rivulets of moisture on the blade surface can be seen in the film although the quality of the film was not sufficient to rule



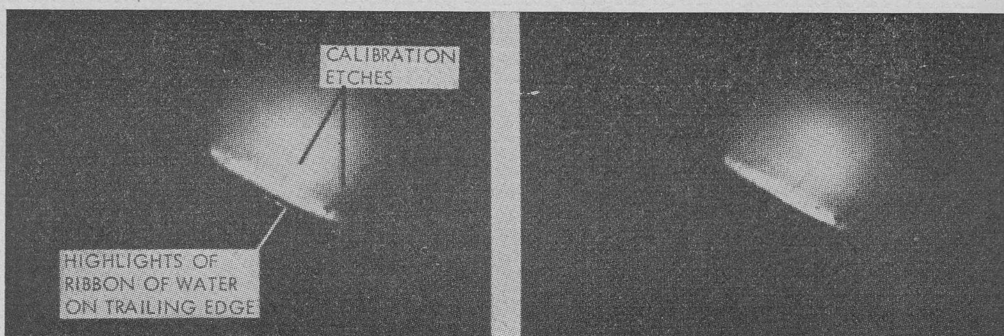


Fig. 13. Photos–pressure surface view

out the possibility of a thin film existing over most of the blade surface. It can be stated, however, that the condensate collected on the concave surface does not move to the trailing edge in the form of rivulets and perhaps a major portion of the condensate is swept towards the end walls due to secondary flow.

Trailing edge view

Figure 14 orients the viewer for the trailing edge view. This view proved to offer the most informative qualitative information. Large drops could be seen being shed from the trailing edge and in some series of frames drop breakup can be observed. The predominant amount of moisture appears to leave the trailing edge at or near the junction of the trailing edge and casing wall. Since most of the moisture departs the trailing edge near the outer boundary this proved to be valuable information for locating the light tubes when taking backlighted drop photography.

The effects of secondary flow were evident in the direction imparted to the drops leaving the trailing edge near the outer diameter. A strong radially inward velocity is observed in a very consistent manner. Similarly, liquid clinging to the trailing edge moves inward and rather regularly departs the blade at around the 3/4 blade height position. Figure 15 shows a series of frames where, in frame #3, a drop can be seen just prior to departing the trailing edge while in frame #4 drops can be seen near the 3/4 blade height position.

Movies were taken with and without moisture removal and the most significant conclusion reached was that all moisture on the stator blade surfaces was not removed when suction was applied to the trailing edge slots. The amounts of moisture measured externally in the separator system, although admittedly less than that predicted according to the model

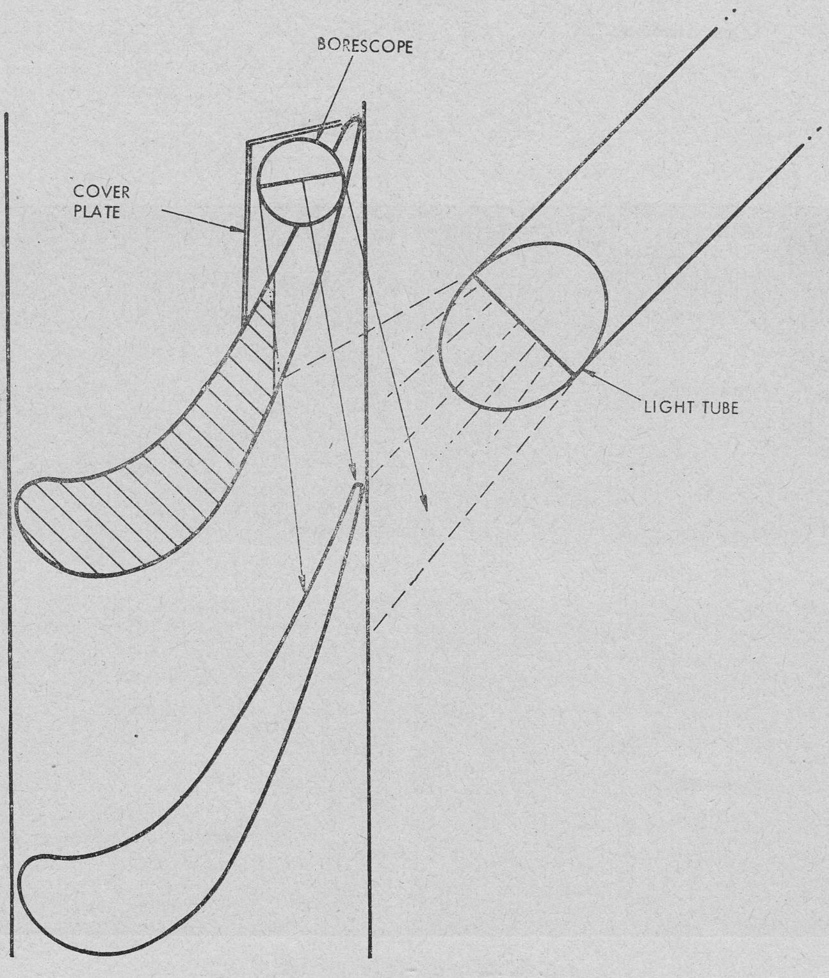


Fig. 14. Trailing edge view–schematic

used, were encouraging and without the film information the conclusions may have been reached that the removal slots were very effective in eliminating large drop shedding from the trailing edge. However, comparison of films with removal on and off showed large drops departing from the junction of blade and casing for both conditions.

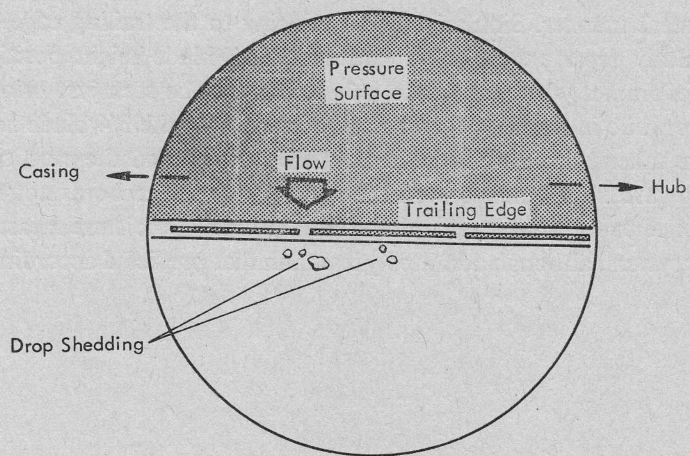


Fig. 15. Photos–trailing edge view

The most likely explanation for the failure of the slots to remove all moisture for this turbine geometry is the strong secondary flows that drag the moisture from the pressure surface across the casing to the suction surface resulting in a concentration in the corner of blade and casing. Shown on Fig. 16 is a schematic of the probable movement of the liquid along the casing wall.

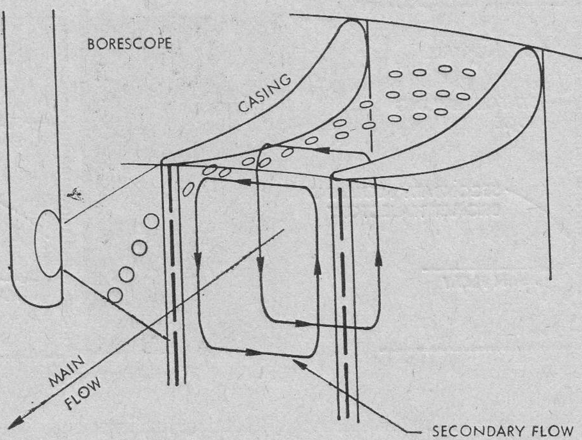


Fig. 16. Secondary flow affect on drop movement

Backlighted drop photography

Shown on Fig. 17 is a schematic of the instrumentation arrangement for the backlighted drop photography. All drop photos were taken with the X 0.2 borescope thus limiting the smallest size of the drops that could be detected to around 60 microns. All movies were

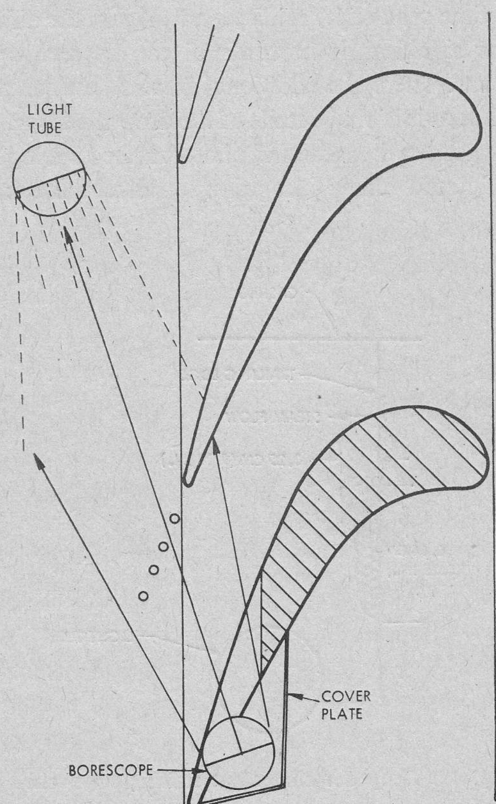


Fig. 17. Plan view for drop photography configuration

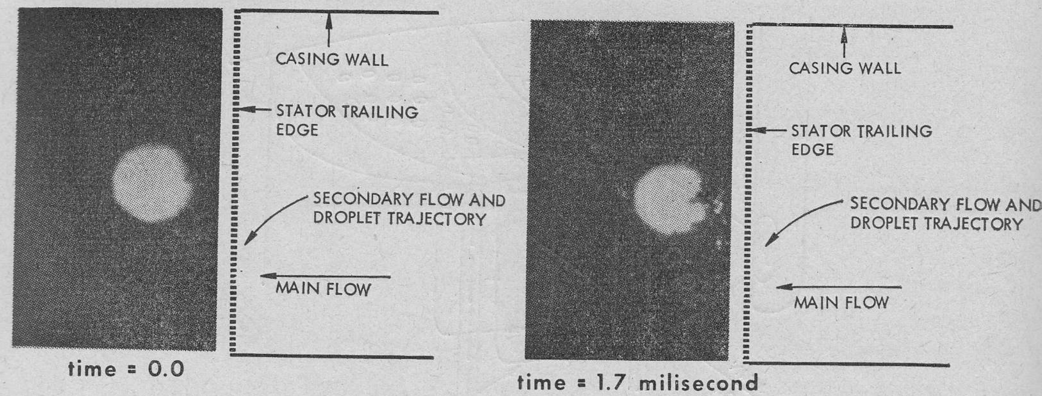


Fig. 18. Backlighted drops leaving trailing edge

taken with a Fastax Camera at 3000 frames/second using both TRI-X and PLUS-X film. The lighting was adequate to give good results with the PLUS-X film which is a more desirable film for measuring the drops.

In some frames of the high speed movies globs of water are seen torn from the trailing edge and in subsequent frames the breakup can be observed. In these instances the radially inward motion of the liquid can be detected. Shown on Fig. 18 are two frames covering a time span of 1.7 milliseconds. Again the difficulties of reproducing the frames are apparent for significantly more detail can be seen upon close examination of the original movie films. There are additional frames between and adjacent to those shown in Fig. 18 which show additional details of the drop shedding. This particular series of frames was the largest concentration of liquid photographed during this test series. Shown on Fig. 19 is a schematic of liquid filmed just prior to detachment from the trailing edge. An estimate was made

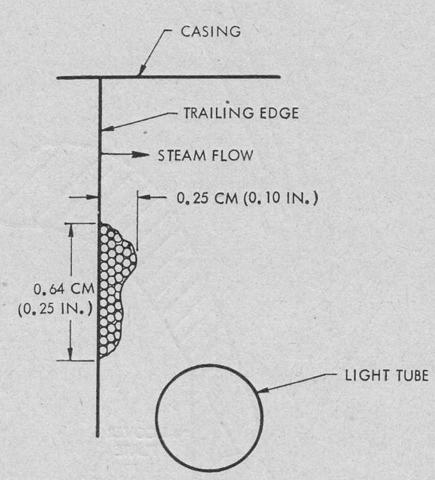


Fig. 19. Drop detachment at trailing edge-schematic

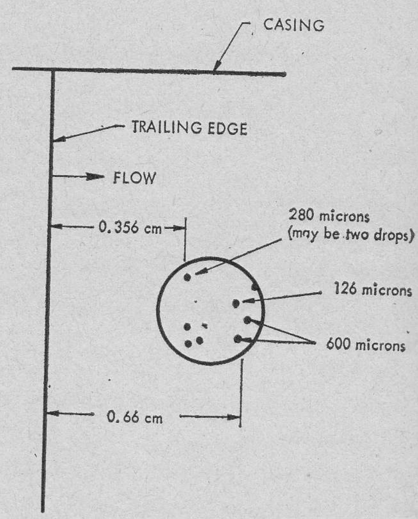


Fig. 20. Backlighted drop measurements-schematic

on a film analyzer of the mass of liquid by tracing the outline formed by the many drops as shown in Fig. 18.

Shown on Fig. 20 is some quantitative measurements taken of drops in front of the circle of light which is the light tube mirror. Qualitative information can be deduced in the "halo" surrounding the light circle. However, the accuracy of quantitative data in this region would be somewhat questionable, even when viewed on a film analyzer, since light reflections give the drops a "soap bubble" appearance indicating the drops may be acting as lenses. Therefore, only drops in front of the circle of light were considered in obtaining quantitative results. In this area the drops appear as black circles. In most frames that were closely examined, the drop diameters were consistent with the theory of drop atomization occurring within 0.5 cm. downstream of the trailing edge. In this particular frame however two drops were measured at 600 microns at 0.66 cm downstream which is significantly larger than expected. Observations of the liquid discharged from the stator were confined to the region between the stator trailing edges and one centimeter downstream. The liquid does indeed depart the stators as rather large globs which are quickly broken up into smaller drops and accelerate from view. A detail difference from that implied by the model is that the globs of liquid undergoing breakup do not move directly downstream but have a substantial radially inwards velocity component due to secondary flow.

6. Moisture removal

Figure 21 shows test results for moisture removal effectiveness through the slotted trailing edges of the 4th stator blade row. Effectiveness is defined as percent of exit equilibrium moisture removed. The moisture removal effectiveness is shown for varying vapor extraction rates. Shown also are the predicted removal rates. The predicted rates were based on moisture collection rates from NASA CR-1830 and 100% removal of all moisture on the outer half of the stator blades. The tested removal rates are less than predicted. Two of the test points were run at the time high speed movies were taken of the stator trailing edge. As discussed in the photographic test results, the movies clearly showed that all moisture on the blade, particularly near the outer diameter, was not removed.

One data point falls close to the predicted removal rate. This test point was the first run for the stator blade removal series but the conditions could never be repeated. The measurement of the moisture removed is believed to be quite reliable. One of the most difficult parameters to measure and control is the turbine inlet temperature. In order to achieve the high moisture levels in the test stage the inlet temperature was maintained as close as possible to the saturation temperature while maintaining superheated conditions. From experience a minimum of 8°C superheat is required.

During a transition period of operation with some less experienced personnel a test was run where the inlet conditions were definitely in the two phase region. The results were most interesting for the trailing edge slots removed six times the predicted removal rate. Unfortunately the moisture level into the turbine was unknown. However, the tests indicated the slots are capable of removing significant amounts of moisture. In view of this experience it is believed the first test point, which falls on the predicted removal rate curve, is higher than the other points due to a slightly wet inlet condition.

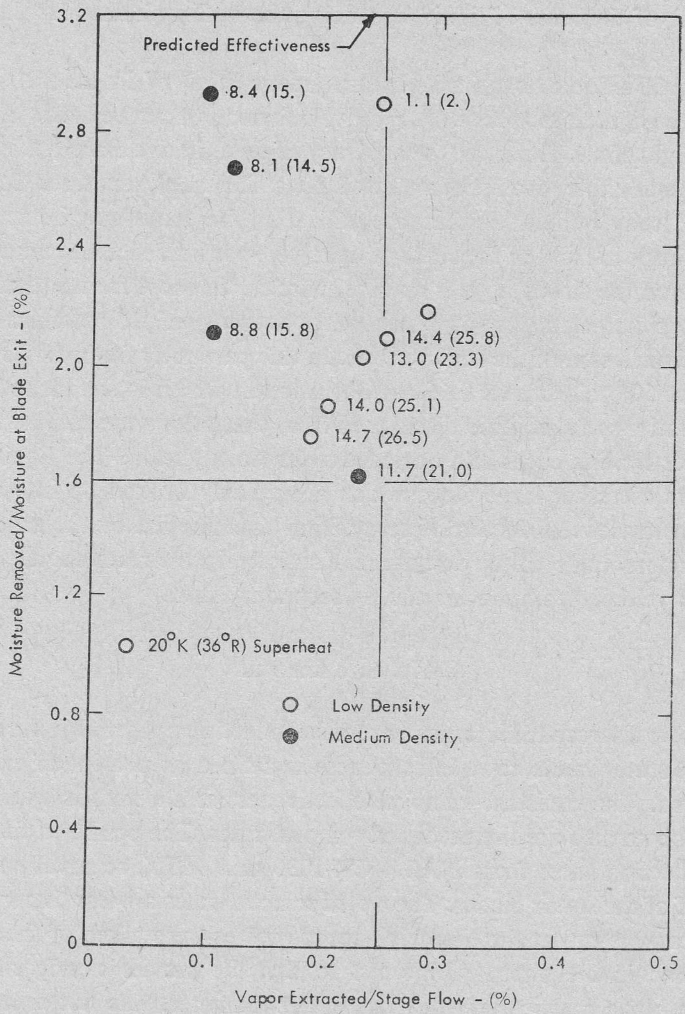


Fig. 21. Moisture removal effectiveness–stator blade slots

The inlet temperature is maintained by a desuperheater. Each data point shown on Fig. 21 has an accompanying number designating the measurement superheat at the turbine inlet. Low superheat appears to have an effect on the results indicating some moisture may have been carried into the turbine inlet from the desuperheater. For the one test point where the effectiveness was very high (not shown on Fig. 21) the inlet was unquestionably in the wet region. This test point, in addition to the apparent effect of inlet superheat, illustrates how different conclusion may be reached as to moisture removal effectiveness when moisture is injected into a test turbine as opposed to when the moisture is naturally formed through the turbine expansion process. The test points centered around 14°C superheat appear meaningful and show a trend of improved moisture removal with increasing vapor removal, contrary to the model assumed.

Shown on Fig. 22 is the removal effectiveness of the casing slots behind the third and

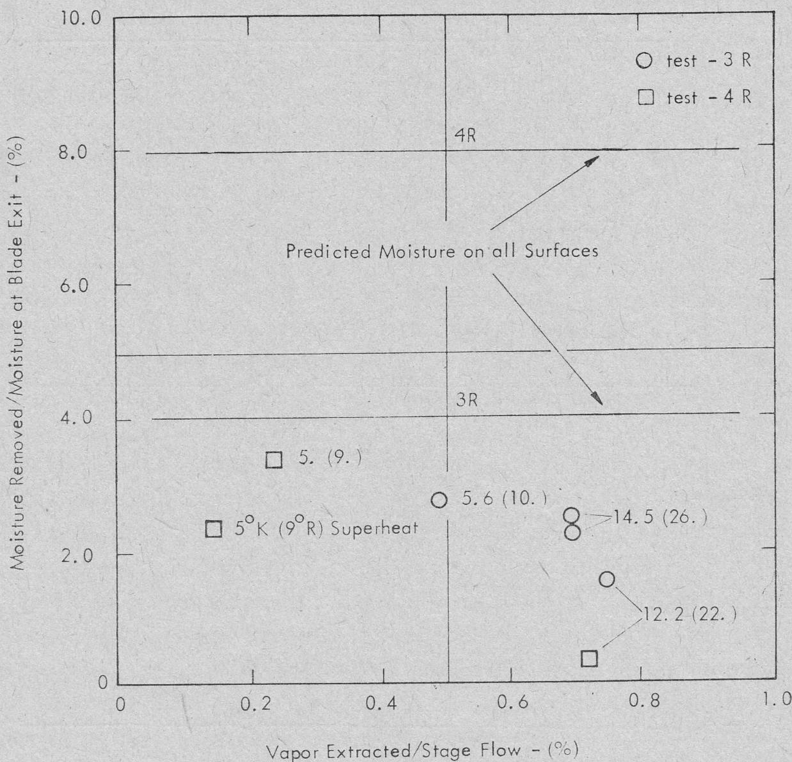


Fig. 22. Moisture removal effectiveness-3R and 4R casing slots

fourth rotor blades. Also shown are the predicted amounts of moisture collected on all turbine surfaces according to the analytical model. The third rotor blade casing slot removed up to 68% of the predicted amount of moisture available. The fourth rotor blade casing slot performance was poor. The same philosophy was followed in the design of the slot and annular collection chamber as in 3*R*. The amount of superheat again appears to be a factor in the 4*R* slot performance and to a much lesser degree in the 3*R* slot performance. The standard speed movies at the fourth rotor blade exit tend to verify the low removal rate of the casing slot.

7. Efficiency

The turbine was not designed nor instrumented with the intention of running a sophisticated performance test program. Likewise, optimum performance was not sought. The original intent was to design a turbine to expand sufficiently far into the two phase region to permit photographic observations to be made. However as the program progressed, it was decided to attempt to estimate moisture effects on turbine efficiency. Performance was measured over a range of moisture levels to determine the thermodynamic degradation due to moisture.

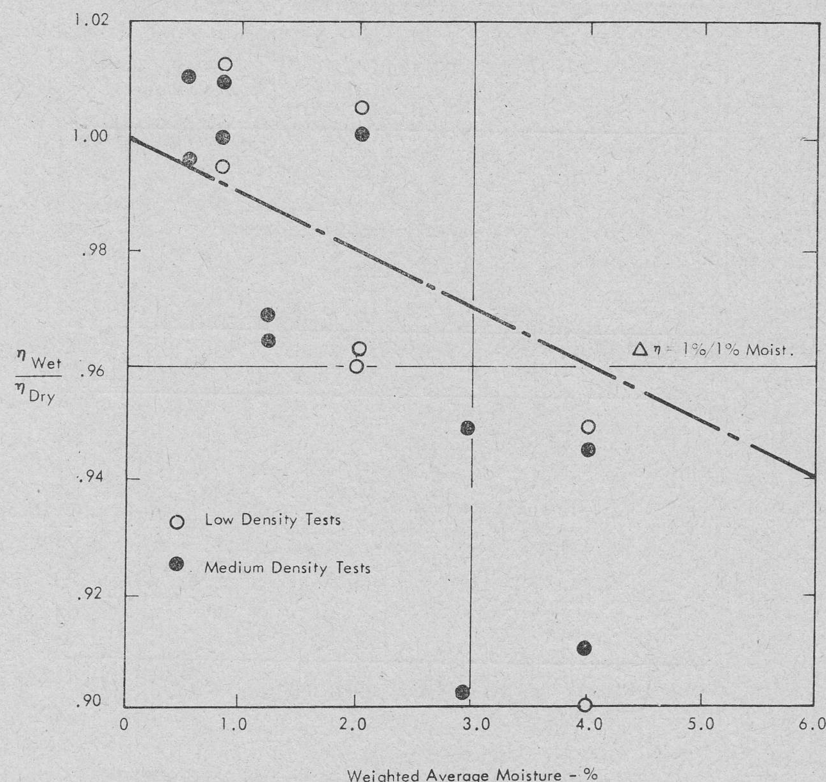


Fig. 23. Efficiency ratio for wet and dry condition

To determine the effects on turbine performance due to moisture other variables that affect performance must be considered and held constant as best possible. Two important parameters are Mach number and flow incidence at blade inlets. Although these parameters cannot be held constant over a range of moisture levels, the effects can be minimized by judicious selection of operating conditions. These conditions were achieved by varying turbine speed from 5900 to 7060 rpm.

Performance tests were run at nominally 1 %, 4 %, 6 % and 8 % moisture levels at turbine exit for two levels of density. Fig. 23 shows the efficiency ratio for the wet and dry conditions up to an average moisture level across the turbine of 4 %. Although there is considerable scatter in the data the deterioration in turbine performance is quite apparent and further, a non linear relationship is indicated. A line for a 1 % efficiency penalty for each 1 % of weighted average moisture is shown.

8. Concluding remarks

Because of the intense fog present in the turbine, both high speed photographic and visual observations of flows on surfaces and the surfaces themselves were difficult to make and analyze (The reproduction of the movie frames for reporting purposes resulted in additional loss of detail). Careful study of the original films, however, led to some useful deductions. In addition, resolution of the larger drops of water detached from the fourth stator, backlighted, was good. Resolution of drops below 60 microns diameter was not possible by the optical and film system used. Results of testing are summarized as follows:

1. The observed moisture flows in this turbine differed from that expected on the basis of previous descriptive material such as that given in NASA CR-1830 in important respects:

– Moisture was not observed on the pressure surface in rivulet form. The possibility of the existence of a thin film of moisture cannot be ruled out by the photographic results.

– Moisture appears to concentrate at the junction of blade and casing and that not torn off moves radially inward along the stator blade trailing edge.

– The large globs of moisture torn from the stator blade trailing edge move radially inwards for a considerable distance before breaking up and moving downstream.

– The moisture leaving the last rotor blade as a fog was uniformly distributed over the field of view. No concentrations of liquid could be seen departing the blade shroud and entering the casing removal slot.

– There was little visual difference in the movement or in the amount of moisture observed departing the stator blade trailing edge with or without trailing edge moisture removal. The quantities of moisture removal through the slots that were determined externally by tank measurement were encouraging. These data could have been erroneously interpreted as indicative of the successful removal of most of the potential damaging moisture if the high speed movies had not shown that large drop shedding persisted when the removal slots were operating.

2. The dimensions of the large globs of liquid departing the stators and the diameters of the largest drops observed after secondary breakup of the globs were in general about the same as values calculated using the method of NASACR-1830, although some exceptions were noted.

3. The amounts of moisture removed during operation of the suction slots in the stator trailing edges was about 70% to 90% of that calculated using the method from NASA CR-1830. However, the points at which 90% were achieved occurred at low turbine inlet superheat conditions. For this reason the 70% level appears more representative.

4. The casing slot over the downstream edge of the 3rd rotor blade shroud removed nearly 70% of the moisture available according to the method from NASA CR-1830. The 4th rotor blade casing slot removed very little moisture. Since the design philosophy for the 3rd and 4th casing slots was the same there is no obvious explanation for the discrepancy in the relative performance.

5. Turbine performance measurements over a range of moisture levels indicate a non-linear relationship between moisture level and performance degradation.

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Badanie przepływu w turbinach na parę mokrą

Streszczenie

W turbinach na parę mokrą woda powstająca i gromadząca się na powierzchniach łopatek i kadłuba zmniejsza wydajność turbiny i może doprowadzić do poważnych uszkodzeń łopatek wirnikowych i bandaży wiążących. Celem pogłębienia wiedzy o przepływie dwufazowym w turbinach na parę mokrą, prowadzono próby w wielostopniowej turbinie parowej, pracującej w pewnym zakresie warunków roboczych.

W artykule omawia się turbinę, użytą aparaturę fotograficzną, program prób oraz wyniki prób obejmujące:

– obraz przepływu pary mokrej ustalony za pomocą szybkoobrotowych kamer filmowych oraz fotografii i bezpośredniej obserwacji wzrokowej,

– skuteczność usuwania wilgotności za pomocą szczeliny w kadłubie oraz szczeliny na krawędzi spływu łopatki kierownicy,

– ocenę wpływu strat, wynikających z obecności wilgoci, na działanie turbiny.

Исследование течения во влажнопаровых турбинах

Резюме

Вода, образующаяся и собирающаяся на поверхности лопаток и корпусов влажнопаровых турбин, вызывает уменьшение их мощности и может привести к значительным повреждениям рабочих лопаток и связывающих бандажей. С целью углубления знания о двухфазном течении во влажнопаровых турбинах, проводились испытания многоступенчатой паровой турбины, работающей на переменном режиме. В статье описываются: турбина, применяемая фотографическая аппаратура, программа и результаты испытаний, охватывающих:

– картину течения влажного пара, определяемую методами быстрой кинематографии, а также фотографии и непосредственного зрительного наблюдения,

– эффективность устранения влаги через щели в корпусе на кромках направляющих лопаток,

– оценку влияния потерь из-за наличия влаги на работу турбины.