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UMICH 012449-1-T

STEAM TUNNEL INITIAL OPERATION AND RESULTS

by

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Financial Support Provided by:

National Science Foundation

Grant No. GK-40130

January 1974

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ABSTRACT

Preliminary testing of the University of Michigan low pressure wet steam tunnel is reported. It was found that maximum velocity at present is about 1500 f/s giving approximately Mach 1 in the test section. It is expected that modifications and improvements now underway may increase the maximum velocity to about $M = 1.5$. Water films upon blading sections installed in the test section have been induced both by internal cooling of the blade and by injection of water along the blade surface. The behavior and break-up of this film have been observed photographically, along with the droplet size and distribution entrained in the wake. A steam flow separation and reverse flow pattern has been observed along the tapered portion of the blade near the trailing edge. This appears to cause a temporary delay in water film removal, so that the droplet size when removal does occur is increased, thus increasing the erosion problem for downstream moving blades. Thus research upon the effect of the pressure gradient near blade trailing edge upon entrained droplet size could bear fruit in helping to alleviate the blading erosion problem.

I. INTRODUCTION

Present-day nuclear reactor powerplants, stationary, marine, or airborne, are usually distinguished from their fossil-fueled counterparts by their low-temperature steam conditions, usually lacking in both superheat and reheat. The net result is an aggravated turbine moisture problem in the low-pressure stages, leading to both severe erosion problems as the liquid droplets impact the turbine blades with a very high relative velocity, and to an overall loss of efficiency due to the two-phase nature of the flow. These problems are also severe and partially limiting in fossil-fueled plants, particularly as power outputs are increased, increasing the diameter of the turbines at the low-pressure ends, and hence the blade speeds due to the requirement of a fixed rpm condition. However, for the same power output, these problems are much more severe for nuclear plants due to the lack of superheat and also reheat in some prevalent types.

The same problems arise in liquid metal turbines of interest for nuclear-space power (SNAP) and hence these studies, using a new steam tunnel in our laboratory, will provide information pertinent to this field also.

We have recently designed and erected a low-pressure "steam tunnel" with transparent test section, designed for wet-steam conditions similar to those existing at the low-pressure end of present-day large nuclear-plant turbines (1), and with realistic target steam velocities (250 to 300 m/s). (Figs. 1 and 2). Wet steam flows across selected

profiles similar to turbine stator blading. The formation of droplets from the liquid film which will deposit on the profiles from the wet-steam stream are then observed photographically. This report describes the tunnel in detail and presents initial results obtained. In addition projected future work is discussed.

II. TEST FACILITY

1. Steam Tunnel

Figure 1 shows the physical arrangement of the steam tunnel. Point 1 is the inlet point for saturated steam from the building heating system. At point 2 pressure and temperature are monitored. From these values plus the differential pressure across an orifice mass flow rate can be calculated. Point 3 indicates a stilling tank just upstream of the test section. Injected water can be added into the stream if desired, in this stilling tank to produce the desired steam quality in the test section. The steam next passes through a nozzle into a constant area test section where profiles to be studied can be attached. After this test section, the diffuser allows recovery of some of the kinetic head, to allow maximum test section velocity before entering the condenser. In the open condenser, cold water is mixed with the steam to provide a minimum back-pressure. Two vacuum pumps are used to remove air, largely carried with the steam, from the condenser, test section, piping, and stilling tank. Instrumentation is available also for stilling tank temperature and pressure, volume and temperature of water injected into the steam.

2. Test Profiles

Currently two different test profile blades have been used. Both have the same exterior shape. However, one includes a slit across the front part of the blade (perpendicular to the steam flow), Fig. 2. Water can be introduced through this slit to produce a water film on the blade surface. Varying the water inlet will then give different water flow rates.

The second blade has in place of the slit a cooling chamber across and within the blade (Fig. 3). Cooling water is passed through this sealed cooling chamber to lower the blade surface temperature. Along the blade surface steam condenses generating a natural water film to flow along the surface of the blade, somewhat similar to analogous processes in a turbine. To increase the surface film thickness the water flow rate through the cooling chamber can be increased. One factor with this blade design is the somewhat uneven cooling across it, in that the cooling chamber does not extend all the way to the edges. The effects of this (and perhaps other boundary condition effects) is shown in Fig. 8 where the water film behavior changes drastically near edges of the cooled portion.

3. Flow Parameter Measurements

Two methods for measuring steam velocity in the test section are used: a Pitot tube in the test section, and an upstream orifice. The absolute pressure and pressure differential are of course measured in both cases. For the Pitot tube, there results:

$$V = 5.584 \sqrt{h_w v}$$

where v = specific volume of steam
 h_w = inches of water manometer head
 V = steam velocity - f/s

For the orifice, one obtained (2)

$$W_h = 359 K_o B^2 D^2 F_a F_m F_r Y \sqrt{h_w Y_f^*}$$

where:

K_o = a coefficient of discharge
 B = diameter ratio
 D = correction for temperature expansion of device
 F = diameter
 F^a = manometer correction
 F^m = correction for Reynolds number
 F^r = expansion factor at operating differential
 h = inches of water
 Y^w = specific weight of vapor
 W_h^f = mass flow rate of steam - lbm/hr.

$$W_h = 754.3 \sqrt{\frac{h P_f}{T_f}}$$

where:

T_f = temperature of steam ($^{\circ}$ R.)
 P_f = upstream pressure, psia

The steam velocity in the test section is then:

$$V = W_h \cdot v \cdot 1/A$$

A = area of the test section
 v = specific volume of steam

In comparing results from these with the two methods of velocity measurement results are within $\pm 15\%$ error, with the Pitot tube being the higher of the two. We believe the orifice method is probably the more precise of the two because of the known difficulties with impact tube measurements in two-phase flows.

The maximum velocity attained in the test section during operation was about 480 m/s., giving a Reynolds number of $\sim 0.5 \times 10^5$. Thus the main steam flow is always turbulent, but of course there remains a laminar boundary layer around the blade.

4. Test Results

a. Injected Water Film

Figure 4 shows surface waves in the water film along the blade. It appears that these waves originate at the point where the taper begins. This is also seen in Fig. 5 for a smaller water injection rate. Here the wave covers nearly the entire width of the blade. Both photos show a much smoother film flow before the taper. This is observed and discussed later in connection with the water-cooled blade.

The top of Fig. 6 shows a fairly large portion of the water film being torn away by the steam flow. The detailed formation of water droplets is shown and their later dispersion. An interesting difference in the mode of the tearing away of the film can be seen by comparing the top of Fig. 7 with that of the top of Fig. 6. The torn off portion in Fig. 7

clearly does not disassociate into droplets until the stream is some distance from the end of the blade. Before droplet formation the stream also seems to twist as it leaves the blade. The angle of separation of the droplets after droplet formation further suggests some form of vortex.

b. Condensed Water Film

Figure 8 shows the film streaming effect at the edges of the cooling chamber. The coverage of the small holes that are to the left of the photograph indicate the edges of the cooling chamber. Outboard of these points the even film flow begins to break into streams. These streams flow very uniformly until they approach the blade trailing edge at which point they collect. This is also seen in Fig. 9. After this collecting the tearing away of relatively large water slugs, is very irregular and uneven, accounting for the larger droplet size in the wake downstream.

Figure 10 is an enlargement of the region where the film terminates and collects. It also shows how the condensed film builds up all the way to the edge of the blade. At the time of this photo, droplets were breaking off only in a few places. This can be more easily seen in Fig. 11. Only one small stream is leaving the blade, whereas the rest of the streams are collecting. This collecting effect suggests that flow separation has occurred at the start of taper so that there is an upstream velocity component along the blade in this region, presumably due to the blade taper. Thus

it is possible that modification of the blade shape in the region of the trailing edge could reduce the flow separation and perhaps also the resultant droplet size in the wake. This would of course be highly desirable from the viewpoint of reduced erosion.

Further research with this finding could help to reduce the collecting effect, thus reducing droplet size.

Figure 12 was used to obtain a rough estimate of the droplet size in the wake of the blade. A comparison of the photographic size of the Pitot tube, seen in the middle of Fig. 12 to its actual size was used.

The larger drops were found to be 0.055-0.11 mm diameter.

III. TENTATIVE FUTURE PROGRAM

After having finished the preliminary test runs and carried through some investigations possible with the available instrumentation and facility limitations, it is time to reflect what can be done to improve the test facility, and what should be investigated in the future.

The improvement of the test facility can be divided into two parts; 1) improving the tunnel, and 2) improving the instrumentation.

1) Tunnel

The previous test runs showed that the water condensate pump cavitates at test section pressures of about 3.2 psia, thus limiting condensor pressure and steam velocity in the test section to the values obtained and already discussed. A lifting of the condensor unit by 5 feet should allow lowering the pressure in the test section to about 1.2 psia and thus reaching

substantially higher steam velocities. A more powerful vacuum pump would also help to reach these conditions. These improvements are now being carried out.

2) Instrumentation

In view of the planned future investigations, more sophisticated instrumentation would be appropriate. The flow pictures already taken with a conventional camera demonstrate that for a precise evaluation of the droplet spectrum it would be necessary to take pictures of the two-phase flow with the help of a microscopic lens. Especially for the very small droplets, the quality of the photographs taken with normal lenses is not good enough to read off their size.

The light scattering method is another possible way of evaluating the droplet size spectrum. It is being used at present in this laboratory to measure the cavitation nuclei spectrum in water. In principle, all necessary instruments are already available in this department, i. e., a laser, a photomultiplier, and a multichannel analyzer. At the high velocities in the steam tunnel test section the resulting photomultiplier pulses would be in the order of 1 usec, so that the multichannel analyzer could be used directly for processing the pulses, i. e., without preparing the pulses in some way (e. g. shaping) before being processed. A possible difficulty is the avoidance of condensation at those points of the test section where the laser beam enters, and the scattered light to the optical receiving system (photomultiplier) leaves the test section. By locally heating these

"windows" that problem can be solved.

For measuring the individual droplet velocities, the so-called laser Doppler velocimeter could be used. That method utilizes the shift of the frequency of the laser light scattered from the moving droplets, in order to evaluate their speed. It would thus allow the measurement of the velocity profile over the test section, as well as the turbulence in the wake of the test body.

A combination of both measuring procedures, i. e., droplet size and number, and droplet speed, would allow then an evaluation of the quality of the two-phase flow. This could be also done perhaps by gathering the droplets with an isokinetic probe held into the flow or with a "steam calorimeter".

With the improved instrumentation, a research program for the investigation of the flow pattern behind a test body in a high-velocity two-phase flow may be carried through by varying the following parameters:

1. The static pressure in the test section and thereby the steam velocity
2. The water flux over the surface of the plate
3. The temperature of the cooled plate by altering the cooling water temperature or flow-rate to the blade
4. The steam quality by altering the amount of cooling water injected into the saturated steam.
5. The shape of the trailing edge of the blade

Of most interest for this investigation would be the size distribution of the droplets in the aerodynamic wake of the blades as a function of the steam velocity and steam conditions. The results obtained may constitute

a basis for considering a generalized dimensionless relationship between the parameters of the size distribution function of the droplets and a set of Reynolds, Mach and possibly Weber numbers.

IV CONCLUSIONS

A first series of tests has been completed in our low pressure wet steam tunnel to study the behavior of the liquid film deposited on a blade profile shape installed in the test section. A maximum steam velocity of about 480 m/s (~ 1500 f/ε) was attained in these tests with the minimum attainable throat pressure of ~ 3 psia. Test section Mach number is then ~ 1.0 . It is anticipated that improvements and modifications now being made to the tunnel may increase this maximum velocity by up to 50%, thus allowing a complete exploration of the range of interest for the low pressure end of large steam turbines.

Water films upon interposed blade profiles have been induced by internal water-cooling of the blade, as well as by the injection of a water film along the blade. Photographs of these water films have been taken indicating the existence of surface waves in the film, as well as an apparent region of steam flow separation and reverse flow along the tapered trailing edge region of the blade. This reverse flow appears to restrain the tearing-off of the water film, so that eventual relatively large droplets are removed, and entrained in the main steam flow. Thus this steam flow separation and reverse flow behavior near the blade trailing edge could worsen the erosion problem for a downstream moving blade by increasing the entrained droplet

size. Hence, a study of the effect of blading pressure gradients near the trailing edge upon liquid film break-up and droplet size could be fruitful in finding methods for alleviating the erosion problem.

Photographs also indicate the mean entrained droplet size for various steam conditions as well as the distribution of droplets. Maximum droplet size so far is ≈ 0.1 mm diameter. Droplet distribution appears to be influenced by local vortices apparently existing in the steam wake.

V. REFERENCES

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2. L. K. Spink, "Principles of Flow Meter Engineering," Foxborough Co., Foxboro, Mass, 1958.

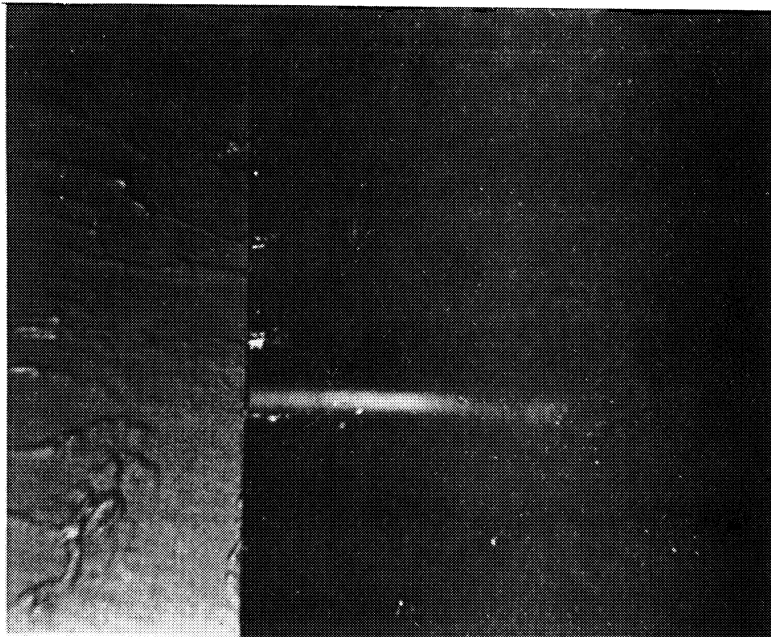


Fig. # 10 - condensed water film

steam velocity-415 m/sec.
film flow rate-120 cc/min.

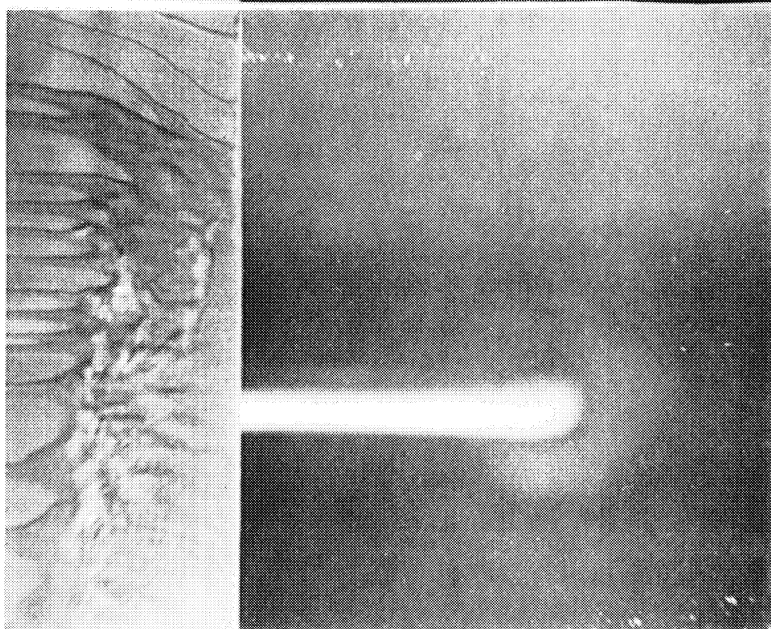


Fig. # 11 - condensed water film

steam velocity-415 m/sec.
film flow rate-120 cc/min.

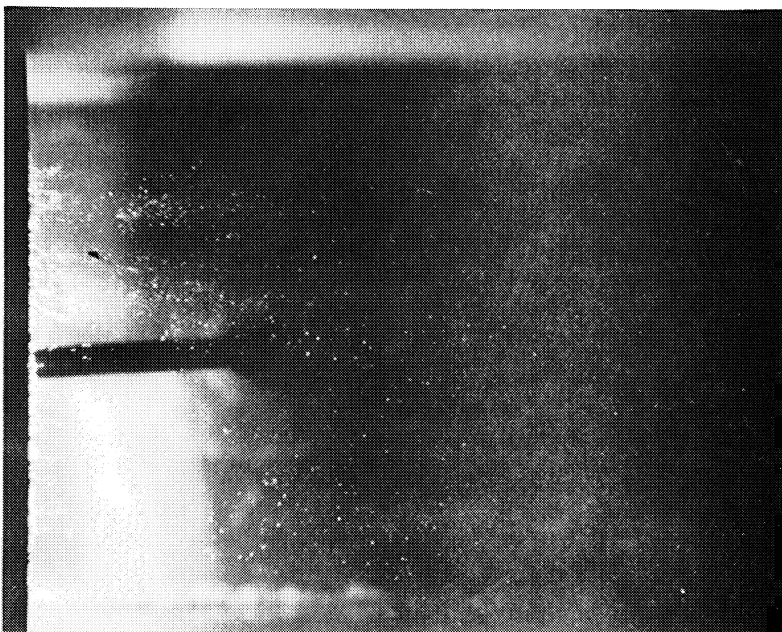
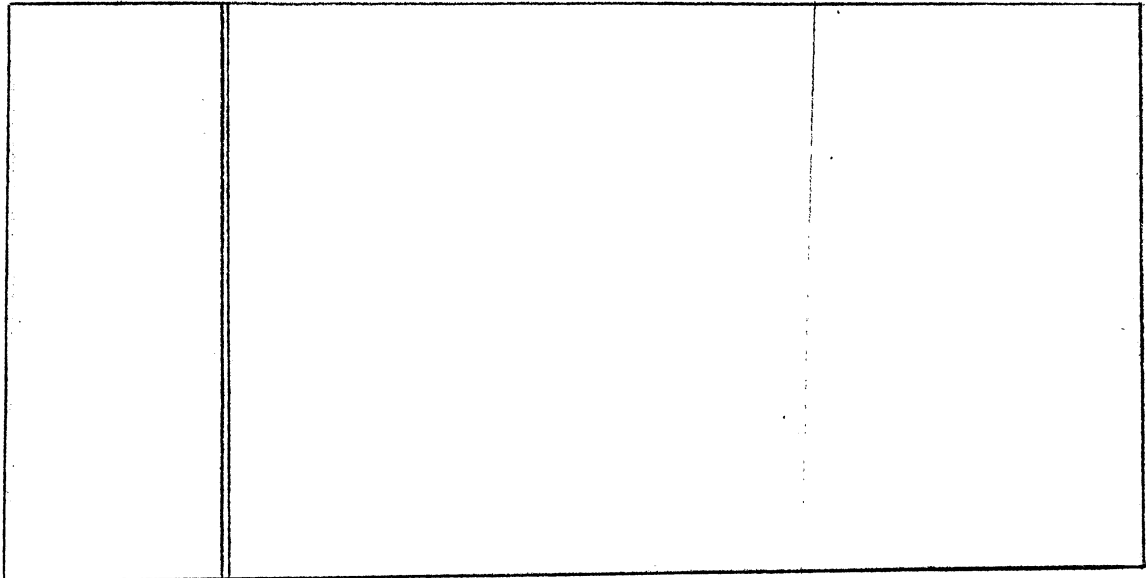
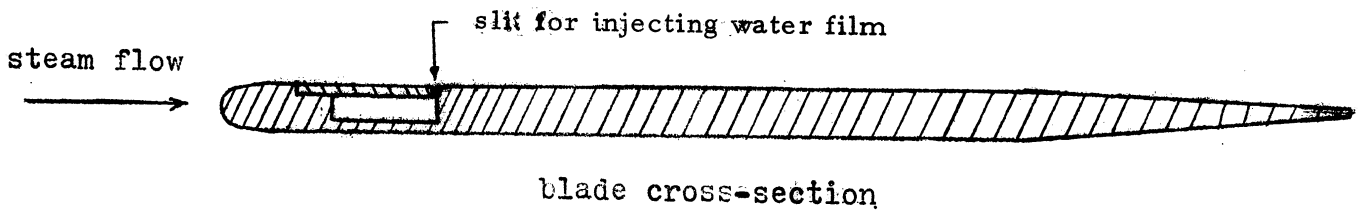


Fig. # 12 - injected water film

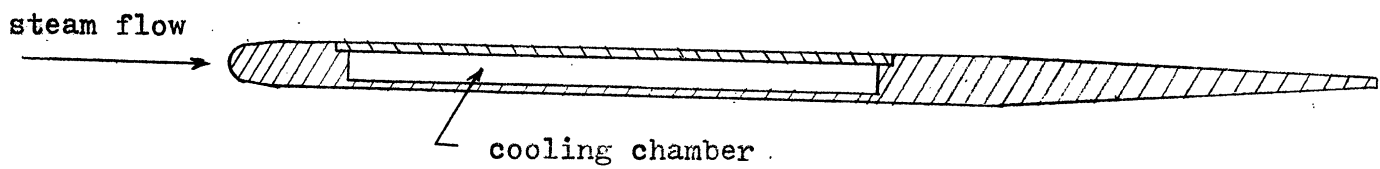
steam velocity-445.4 meters/sec.
film flow rate-20 cc/min.



MATERIAL - stainless steel
 SURFACE - polished

Blade Profile with Injected Water

Figure # 2



MATERIAL - stainless steel
 SURFACE - polished and cleaned

Blade Profile with Internal Cooling

Figure #3

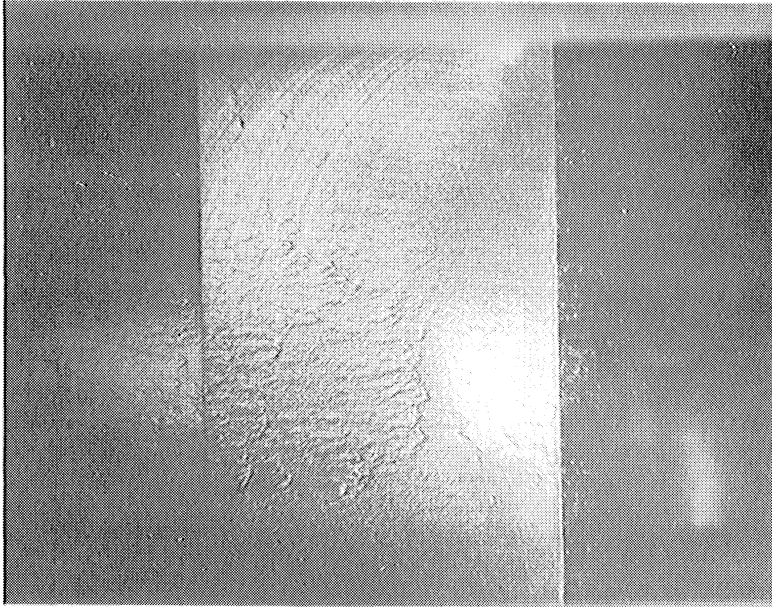


Fig. #4 - injected water film
steam velocity-437.8 meters/sec.
film flow rate-20 cc/min.

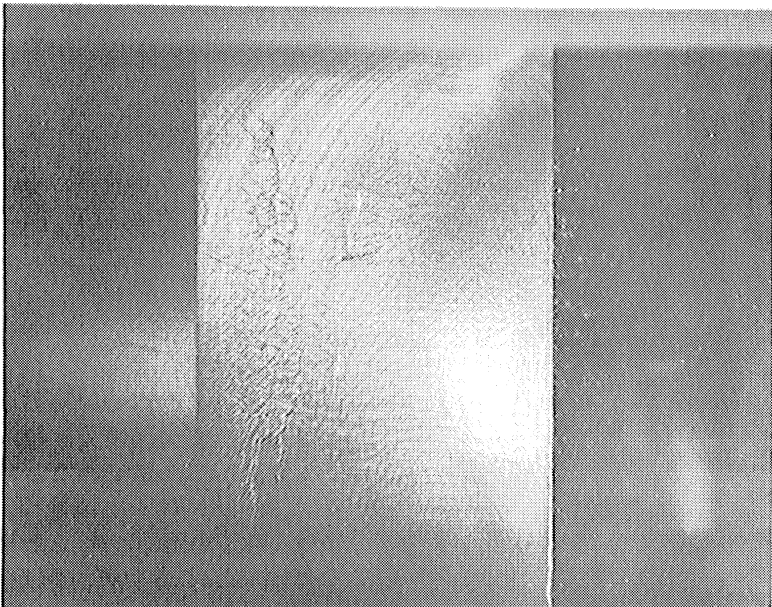


Fig. #5 - injected water film
steam velocity-437.8 meters/sec.
film flow rate-10 cc/min.

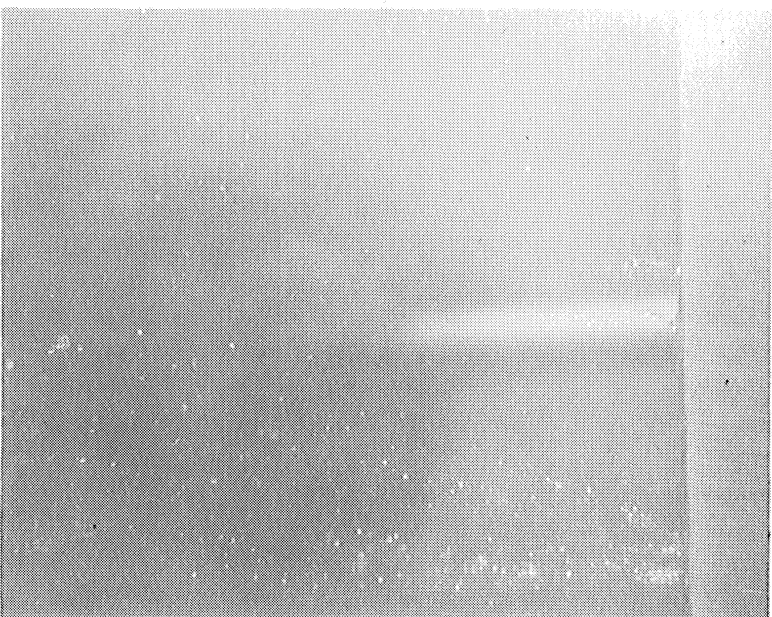


Fig. #6 - injected water film
steam velocity-229.14 m/sec.
film flow rate-30 cc/min.

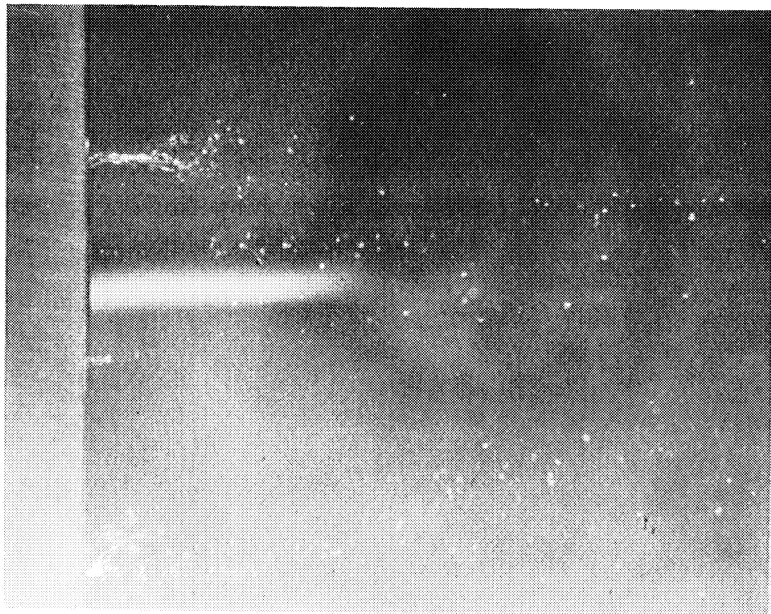


Fig. #7 - injected water film

steam velocity-229.14 m/sec.
film flow rate-21 cc/min.

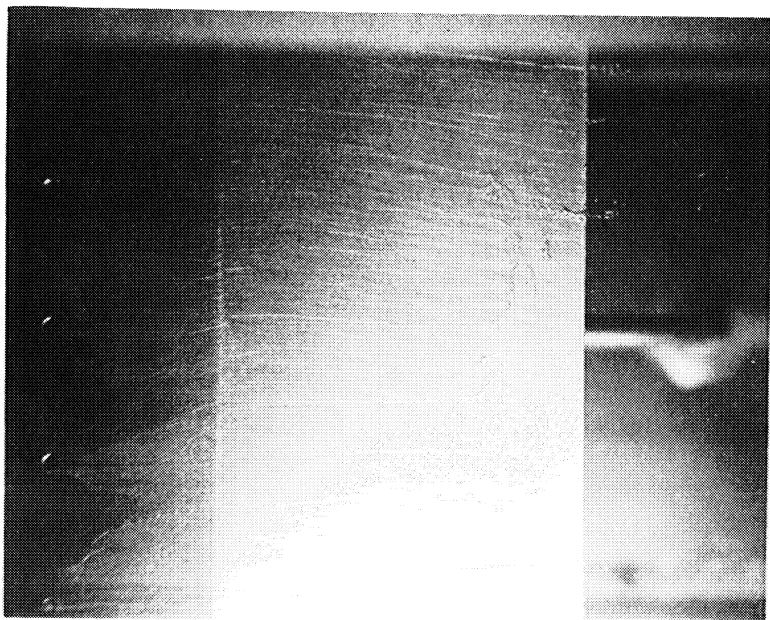


Fig. #8 - condensed water film

steam velocity-415 m/sec
film flow rate-120 cc/min

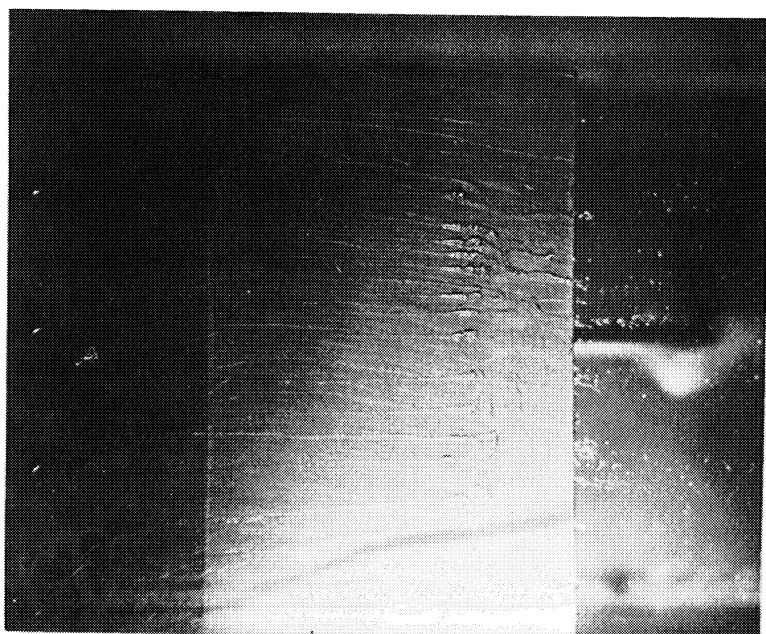


Fig. #9 - condensed water film

steam velocity-415 m/sec
film flow rate-120 cc/min.