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REPORT No. 806

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AN INVESTIGATION OF BACKFLOW PHENOMENON IN CENTRIFUGAL COMPRESSORS

By WILLIAM A. BENSER and JASON J. MOSES

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft (or mi)
Time	t	second	s	second (or hour)	sec (or hr)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb
Power	P	horsepower (metric)		horsepower	hp
Speed	V	kilometers per hour	kph	miles per hour	mph
		meters per second	mps	feet per second	fps

2. GENERAL SYMBOLS

W Weight $=mg$

g Standard acceleration of gravity $=9.80665\ m/s^2$ or $32.1740\ ft/sec^2$

m Mass $=\frac{W}{g}$

I Moment of inertia $=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ Coefficient of viscosity

ν Kinematic viscosity

ρ Density (mass per unit volume)

Standard density of dry air, $0.12497\ kg\text{-}m^{-4}\text{-}s^2$ at 15° C and 760 mm; or $0.002378\ lb\text{-}ft^{-4}\ sec^2$

Specific weight of "standard" air, $1.2255\ kg/m^3$ or $0.07651\ lb/cu\ ft$

3. AERODYNAMIC SYMBOLS

S Area

S_w Area of wing

G Gap

b Span

c Chord

A Aspect ratio, $\frac{b^2}{S}$

V True air speed

q Dynamic pressure, $\frac{1}{2}\rho V^2$

L Lift, absolute coefficient $C_L=\frac{L}{qS}$

D Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_0 Profile drag, absolute coefficient $C_{D_0}=\frac{D_0}{qS}$

D_i Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

i_w Angle of setting of wings (relative to thrust line)

i_t Angle of stabilizer setting (relative to thrust line)

Q Resultant moment

Ω Resultant angular velocity

R Reynolds number, $\rho\frac{Vl}{\mu}$ where l is a linear dimension (e. g., for an airfoil of 1.0 ft chord, 100 mph, standard pressure at 15°C, the corresponding Reynolds number is 935, 400; or for an airfoil of 1.0 m chord, 100 mps, the corresponding Reynolds number is 6,865,000)

α Angle of attack

ϵ Angle of downwash

α_0 Angle of attack, infinite aspect ratio

α_i Angle of attack, induced

α_a Angle of attack, absolute (measured from zero-lift position)

γ Flight-path angle

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AN INVESTIGATION OF BACKFLOW PHENOMENON IN CENTRIFUGAL COMPRESSORS

By William A. Benser and Jason J. Moses

SUMMARY

An investigation has been conducted to determine the nature and the extent of the reversal of flow, which occurs at the inlet of centrifugal compressors over a considerable portion of the operating range. Qualitative studies of this flow reversal were made by lampblack patterns taken on a mixed-flow-type impeller and by tuft studies made on a conventional centrifugal compressor. Quantitative studies were made on a compressor specially designed to enable surveys of angularity of flow, static and total pressures, and temperatures to be taken very close to the impeller front housing.

The results of this investigation showed that the amount of reversed flow definitely increased as the load coefficient of the compressor was decreased and that, in extreme cases, the reversed flow extended several diameters into the inlet pipe. It was found that the principal factor affecting this backflow was the value of the load coefficient at which the compressor was operating. Evidence was obtained which showed that the backflow was not confined to the clearance space between the impeller-blade tips and the impeller front housing but actually extended into the impeller passage. It was also found that the axial velocity near the center of the impeller-inlet pipe was practically independent of the value of load coefficient. Several effects of backflow on the state of the air at the inlet were observed: a definite increase in inlet-air temperature; a radial temperature gradient at the impeller inlet; a high degree of turbulence; and a definite prerotation, which was particularly large in the outer portion of the impeller-inlet annulus.

INTRODUCTION

It has been generally recognized that, when compressors are operating at low values of load coefficient, a recirculation of air occurs in the region of the compressor inlet (reference 1). Because at all times, an adverse pressure gradient will exist from the impeller inlet to the blade tips, the occurrence of a reversed flow must be the result of this pressure gradient exceeding that which can be overcome by the momentum of the forward flow. A reversed flow or recirculation has frequently been evidenced by a definite temperature rise between the orifice tank and the compressor-inlet measuring stations when standard compressor investigations are made at low volume flows. Such abnormal compressor characteristics as excessively high values of slip factor at low values of load coefficient and surge-free operation at extremely low volume flows have been attributed to recirculation. These assumptions have been based on the fact that the occurrence of recirculation would increase the effective value of load coefficient at which the impeller was operating, alter the velocity distribution at the impeller entrance, and increase the inlet temperature. The term "backflow" is used herein to denote recirculation and is defined as any reverse flow along the impeller front housing or in the inlet duct.

In order to determine the nature and magnitude of the effects of backflow on the flow at the impeller inlet, preliminary investigations were made during 1942 at the NACA Langley Field laboratory on two compressors. The first investigation was on a mixed-flow-type impeller in which lampblack patterns were used to study the development and extent of backflow. Although these studies definitely showed the existence of a large amount of backflow at low values of load coefficient, they did not show the complete effect of this backflow on the flow distribution at the impeller inlet. Visual studies or surveys were necessary to obtain additional information of the effects of backflow on the flow at the inlet.

The construction of the mixed-flow unit, however, is such that important alterations would have been required to conduct studies of this type. A conventional centrifugal compressor was therefore used to determine the nature of the backflow in the inlet pipe. For these studies, a transparent plastic inlet duct was mounted on the compressor in place of the inlet elbow and tufts were mounted in this plastic duct to study the flow characteristics in the region of the impeller inlet. Severe backflow was shown to exist at very low values of load coefficient.

These preliminary investigations were purely qualitative and showed only the general trends of backflow. In order to obtain quantitative information on the flow at the inlet to the impeller, it was necessary to take surveys just in front of the impeller face. A compressor was specially designed for surveys of this type and consisted of a modified impeller of the type used in the tuft studies, a vaneless diffuser, and a scroll collector. The investigation, which was made at the NACA Cleveland laboratory during 1943 and 1944, on this experimental compressor consisted of surveys of temperature, velocity, and angularity of flow 0.19 inch from the impeller face for various operating conditions.

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APPARATUS

In the preliminary investigations made at the Langley laboratory, lampblack studies were made on an NACA variable-component unit (reference 2) using a mixed-flow-type impeller in combination with a vaneless diffuser of 20-inch outside diameter. A tube of ¼-inch outside diameter located 7 diameters upstream of the impeller inlet was used for the injection of lampblack; the tube extended across the inlet pipe of the unit. Three small holes were drilled in the downstream side of this tube to facilitate the distribution of the lampblack solution, which consisted of 12 grams of lampblack in 4 ounces of SAE No. 10 oil. For this investigation, all instruments were removed from the inlet and outlet pipes with the exception of one outlet total-pressure tube, which was used in adjusting the outlet pressure.

The tuft studies were made on a conventional centrifugal-compressor unit, which was driven in conjunction with a 10:1 speed increaser by an aircraft engine. There were 20 diameters of straight pipe between an 8-inch graduated gate valve used as the inlet throttle and the impeller inlet. The

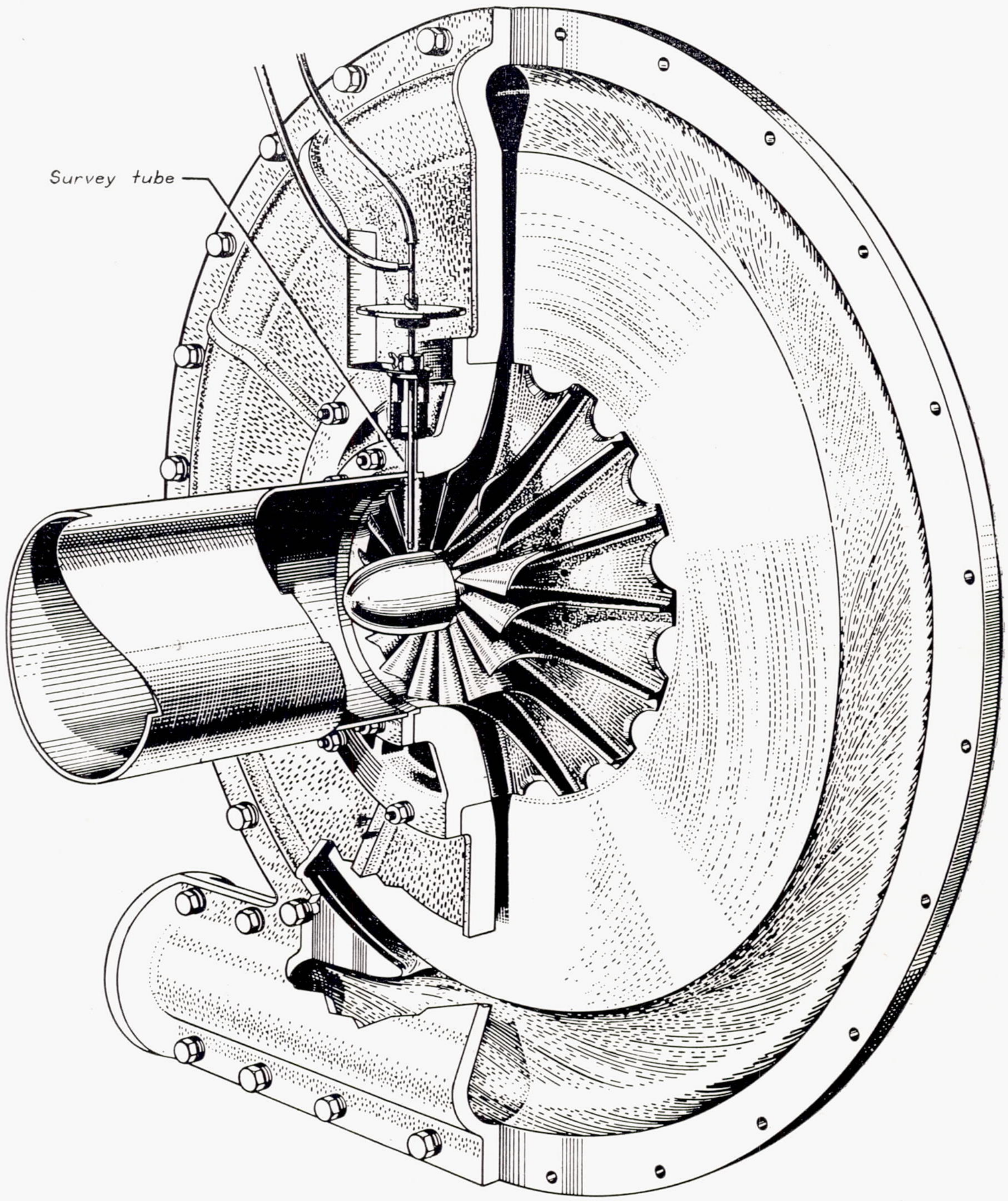
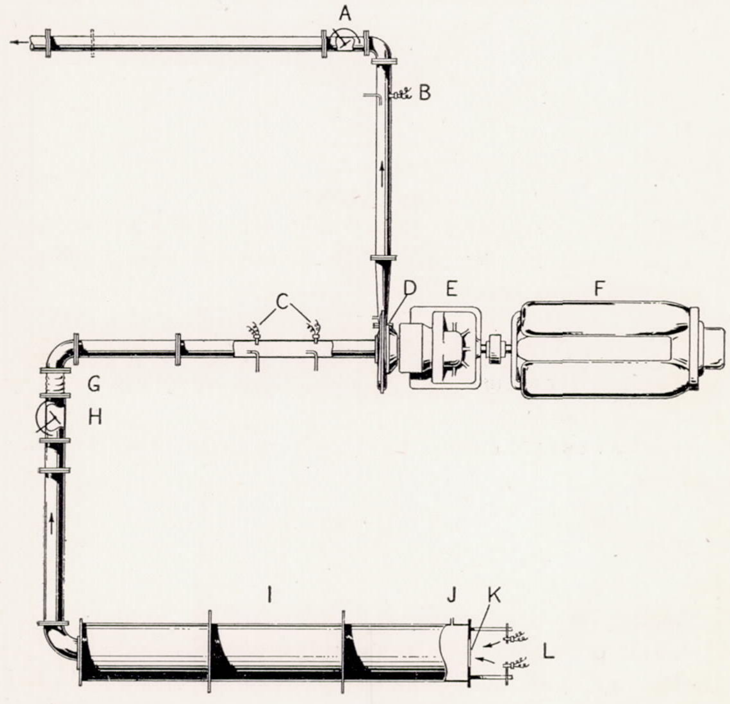


FIGURE 1.—Experimental compressor unit.

3 diameters just ahead of the impeller were made of transparent plastic to enable visual studies of the flow near the impeller inlet. Woolen tufts were mounted on the walls of this plastic duct as well as on strings across the diameter. The compressor unit exhausted through an outlet pipe to the atmosphere. No instruments were installed on this rig.

The surveys at the impeller inlet were taken on the experimental compressor (fig. 1) specially designed for work of this type. The impeller was the same type as used in the tuft studies and had an inlet diameter of 6.250 inches, an outlet diameter of 12.226 inches, and an outlet-blade height of 0.437 inch. A vaneless diffuser and a scroll collector, which were so constructed that surveys could be taken very close



A, outlet throttle
B, outlet measuring station
C, inlet measuring station
D, compressor unit
E, 15:1 speed increaser
F, aircraft engine
G, flexible joint
H, inlet throttle
I, orifice tank
J, orifice static tap
K, orifice plate
L, orifice-inlet measuring station

FIGURE 2.—Schematic diagram of experimental compressor unit.

to the impeller inlet, were used. This compressor unit was driven by an aircraft engine in conjunction with a 15:1 speed increaser (fig. 2). This rig was set up and instruments were installed according to the standard specifications of reference 3. A stroboscopic light and a calibrated speed strip were used for speed determination, and a calibrated orifice plate was used for the air-flow determination.

Surveys of angularity of flow, static pressure, and total pressure at the impeller inlet were made with a 3/16-inch outside-diameter Fechheimer tube (fig. 3). Pressure readings were obtained from two holes that were located 78½° apart and 3/16 inch from the end of the tube. A turntable graduated in degrees mounted at the top of the Fechheimer tube was used to measure the angle at which the tube was set. Temperature measurements were obtained from iron-constantan thermocouples by means of a self-balancing potentiometer. Barometric pressure corrected to 32° F was read from a microbarograph.

METHODS AND CALCULATIONS

Lampblack studies.—The load coefficient Q/n (volume flow, cu ft/revolution) of the compressor for the lampblack pattern was adjusted to the desired value by using the micromanometer reading across the orifice plate and the outlet total-pressure measurement as the indexes. After the unit was run at this condition until complete equilibrium had been obtained, the lampblack solution was injected into the inlet pipe as rapidly as possible. The compressor unit was then run for an additional 20 minutes to bake the pattern. Before the next run, the pertinent parts of the compressor unit were thoroughly cleaned so that each succeeding pattern would represent only the conditions for that run. All patterns

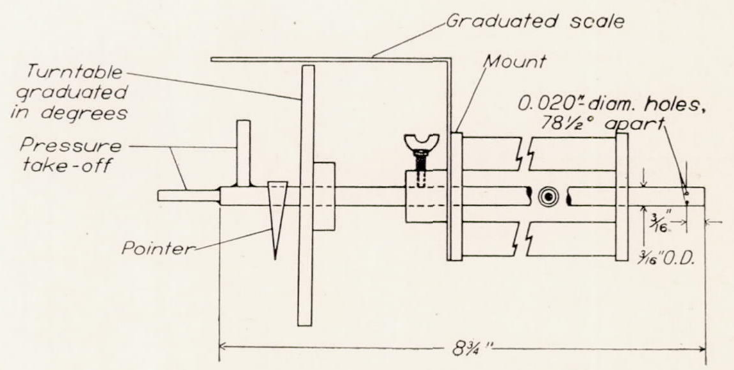


FIGURE 3.—Fechheimer survey-tube assembly.

were made at an impeller-tip speed of 1200 feet per second and at values of Q/n varying from the maximum obtainable to that just above violent surge. The inlet-air temperature for all runs was the ambient room temperature. The outlet total pressure was maintained at 10 inches of mercury above atmospheric, except at very high values of Q/n, in which case the limited capacity of the outlet system produced such a throttling effect that the minimum outlet total pressure obtainable was well over 10 inches of mercury above atmospheric.

Tuft studies.—For the tuft studies, the inlet throttle was first set in the wide-open position and the compressor was run until equilibrium had been attained. The tufts were then photographed using a photoflood light source and an exposure of approximately 0.1 second, which was greater than the period of tuft oscillation and gave an indication of the degree of turbulence and also showed the direction of the mean flow. Because no means of air-flow measurement was provided, it was impossible to determine the exact value of Q/n, but an approximation could be made by comparing the position of the inlet throttle with that of previous calibration runs. Two intermediate runs were made at values of Q/n that were approximately equally spaced between the maximum value of Q/n and the value of Q/n at surge. The final run was made at a value of Q/n that was just above the surge point. All runs were made at an impeller-tip speed of 900 feet per second.

Backflow surveys.—The backflow surveys on the experimental compressor were made at various values of Q/n and at an outlet pressure of 10 inches of mercury above atmospheric and an impeller-tip speed of 1200 feet per second. In addition, surveys were made at impeller-tip speeds of 960 and 1080 feet per second.

For each compressor operating condition, surveys of angularity of flow, static and total pressure, and temperature were taken on a radial traverse that was located 0.19 inch upstream of the impeller face on the top of the inlet pipe (fig. 4).

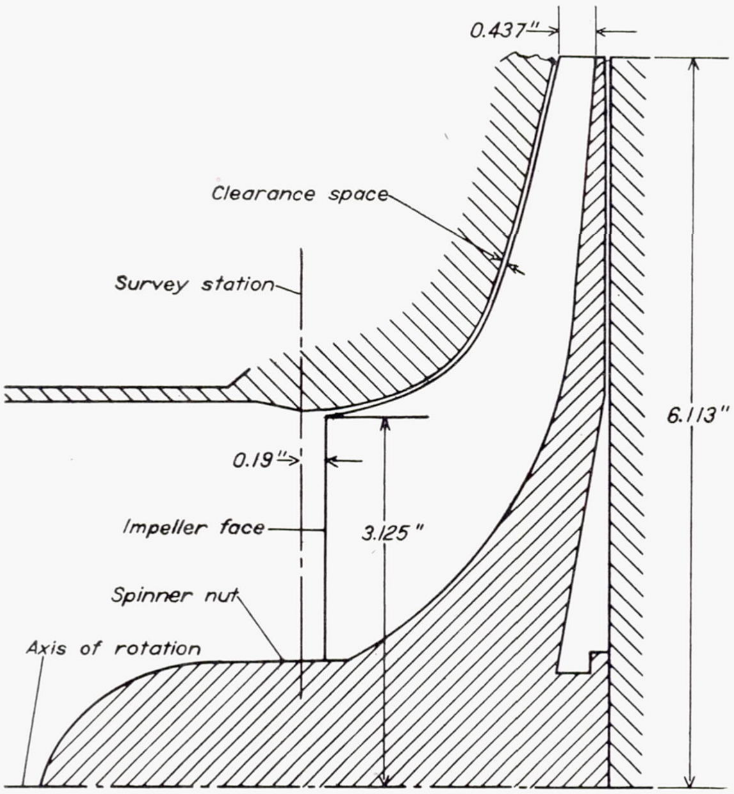


FIGURE 4.—Location of survey station with respect to impeller.

The zero angle of the Fechheimer tube was determined by so inserting the tube in the inlet pipe that a line bisecting the angle between the two holes was parallel with the center line of the inlet pipe. In the pressure and angle surveys with the Fechheimer tube, the tube was adjusted to the proper radius for the point to be taken and then rotated until the pressures from the two pressure taps were equal. Inasmuch as the line bisecting the two holes was then pointing directly into the air stream, the angle of flow could be measured. The static pressure of the air stream at that point was also obtained when the pressures from the two pressure taps were equal. In order to obtain total-pressure measurements, the tube was rotated until a maximum absolute pressure was obtained on one of the taps. This maximum pressure was the total pressure at that point. The temperature surveys were made by inserting an iron-constantan thermocouple in the same instrument location as used for the angle surveys. The thermocouple was adjusted to the desired radius and the temperature read directly from a self-balancing potentiometer.

Before each survey the inlet and outlet throttles were adjusted to give the desired values of Q/n and outlet total pressure. The Q/n value was set using the micromanometer reading across the orifice plate as the index. After the temperatures and operating conditions had become stable, the flow angle, the static pressure, the total pressure, and the temperature surveys were taken at either ¼- or ⅛-inch intervals beginning near the spinner nut and ending close to the wall of the inlet pipe. During the surveys, the speed was kept constant and the throttles were left in position. Standard compressor data were recorded at the beginning of each survey and again at the completion of the survey as a check on the stability of the operating conditions.

The air density was determined from the thermodynamic relation

$$\rho=\frac{p}{gRT}$$

where

ρ density, slugs per cubic foot
p static pressure, pounds per square foot
g acceleration of gravity, 32.174 feet per second per second
R gas constant for air, 53.5 foot-pounds per pound per °F
T observed temperature, °R

The stagnation-temperature rise due to compressibility was neglected because the effect of this correction on the density would be small.

Velocity was calculated from the dynamic pressure q by the equation

$$V=\sqrt{\frac{2q}{\rho}}$$

where

V velocity, feet per second
q dynamic pressure, pounds per square foot

Axial- and tangential-velocity components were calculated by multiplying the cosine and the sine of the angle of flow, respectively, by the total velocity.

PRECISION

The precision of the angle determinations made with a Fechheimer tube is dependent on the turbulence of the flow, the sensitivity of the pressure-measuring devices, and the zero setting of the tube. The flow encountered in these tests was very turbulent, especially at low values of Q/n, and a possibility of small errors existed in balancing the two pressures while making an angle measurement. Consideration of the characteristics of a Fechheimer tube and an examination of the reproducibility of the data indicated that the error in angle measurement induced by these factors is of the order of $\pm$½°. Because of the method used in obtaining the zero setting of the tube, however, the angle reading might have been in error $\pm$2½°; inasmuch as the relative values of angle obtained were considered to be of greater importance than the absolute values, this error in zero setting was unimportant.

The precision of the measurement of static pressure by means of the Fechheimer tube is dependent on the pressure distribution around a cylinder located normal to the direction of air flow. There is, consequently, a possibility of small errors in measurement because the angle at which true free-stream static pressure exists on the surface of the cylinder varies slightly with Reynolds number. This variation is small, however, and the maximum error for the pressure-tap spacing used has been evaluated (reference 4) as 10 percent of the dynamic pressure. Because the dynamic pressure was taken as the difference between the static and the total pressures, this error in static pressure would result in a maximum error of 5 percent in the velocity determination.

Temperature measurements with the system used are accurate to $\pm 1°$ F.

ANALYSIS

Because all flow must be instigated by a pressure gradient, the occurrence of backflow must be the result of a pressure gradient exceeding that which can be overcome by the momentum of the forward flow. At all times, there will be an adverse pressure gradient from the impeller inlet to the blade tips. This gradient will act on the relatively slow moving air in the clearance space and tend to cause a backflow within the clearance space. Although this tendency may have an appreciable effect on the backflow, it does not account for the reverse flow of air from the impeller passages.

In order to determine the pressure gradient along the flow path near the impeller front housing, the summation of the components of three pressure gradients must be considered. These pressure gradients are the result of centrifugal force, curvature of the impeller front housing, and changes in flow area of the impeller passages. Although, in the case of an ideal fluid, the centrifugal force would have no effect on the velocities, the compressible and viscous properties of air render it necessary to consider the effects of this force.

The principal components of the pressure gradients resulting from centrifugal force can be divided into two parts: (1) those resulting from an increase in the radius of rotation of the air, which are independent of any changes in the relative velocity of the flow for equilibrium and, except for the increase in the density of the air with the pressure, may be disregarded in this discussion; and (2) those resulting from an increase in the angular velocity of the air, which are dependent upon a change in relative velocity of the air with respect to the impeller. The pressure gradient must be held in equilibrium by the reduction of the relative tangential component of the velocity of the air. This component of velocity will be just sufficient to maintain equilibrium, and any losses that occur must be at the expense of the momentum of the axial component of velocity. In the conventional-type impeller, this pressure gradient resulting from rotational acceleration will be confined to a region near the impeller inlet and will increase in magnitude with decreasing values of Q/n.

The second pressure gradient to be considered is caused by the curvature of the flow path. In the region where the convex curvature is increasing, this pressure gradient will be adverse.

The third consideration is the rate of change of the effective flow area. If this flow area does not decrease rapidly enough as the density increases, the product of the density and the flow area ρA will increase and the velocity must decrease to maintain continuity. This reduction of velocity will create an adverse pressure gradient along the flow path.

Because these three factors are complexly interrelated, no mathematical solutions can be found for determining the magnitude of the resultant pressure near the impeller front housing. The problem is further complicated by the difficulty encountered in determining the true flow path and flow area throughout the impeller. From a study of the extreme cases of very high and very low values of Q/n, however, the trend of the expected backflow can be predicted.

RESULTS

PRELIMINARY STUDIES

The results of the lampblack and tuft studies are purely qualitative in nature and show only the general trends of backflow. No attempt is made to determine the origin of backflow or to correlate these results with those obtained on the experimental compressor rig.

Lampblack patterns.—The adiabatic-efficiency curve at a tip speed of 1200 feet per second for the mixed-flow-type compressor unit on which the lampblack patterns were made is shown in figure 5. The values of Q/n at which these

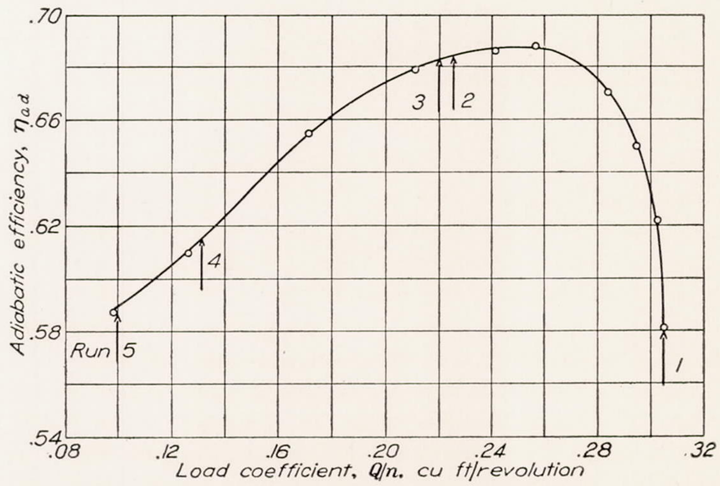


FIGURE 5.—Adiabatic efficiency of mixed-flow-type compressor unit for actual impeller-tip speed of 1200 feet per second and outlet pressure of 10 inches of mercury above atmospheric. (Arrows indicate points where lampblack patterns were made.)

patterns were made are indicated on the curve. Run 1 was made at the maximum value of Q/n obtainable. Runs 2 and 3 were made at Q/n values of 0.225 and 0.220, respectively, because this particular compressor had a small range of light surge between these values.

A photograph (fig. 6) of the lampblack pattern made on the impeller front housing at a Q/n value of 0.305 (run 1) shows that there may be a stagnation of the boundary layer or a limited backflow near the impeller-blade tips. Because the air must at all times rotate in the direction of impeller rotation, backflow is evidenced by a reversal of the component of flow that is normal to the tangential component and is determined from the photographs by a study of the direction of the flow lines.

The pattern made in run 2 at a Q/n value of 0.225 (fig. 7) indicates that at this operating condition a backflow existed from the impeller-blade tips to the impeller inlet but did not extend back into the inlet pipe. Different degrees of backflow occur at four distinct regions. The results of run 3 (fig. 8) also indicate backflow from the impeller-blade tips to the impeller inlet, but the flow lines are continuous. This change in backflow characteristics is probably caused by the change in flow through the compressor. Although the change in Q/n between these two runs was small, the occurrence of the light surge indicated that a considerable change in flow characteristics through the compressor must have taken place.

The patterns obtained on the impeller front housing and the impeller, in run 4, which was made at a Q/n value of 0.132, are shown in figures 9 and 10, respectively. At this operating condition, the backflow starts in the region of the impeller-blade tips and extends approximately 6 inches back into the inlet pipe. The pattern obtained on the impeller shows a very light deposit of lampback near the blade roots (fig. 10). Approximately two-thirds of the distance out from the blade roots there is a heavy lampblack deposit, which is terminated very abruptly. On the outer one-third of the blades, there is a deposit slightly heavier than that near the blade roots. The sharp demarcation between these two regions denotes a cleavage plane in the flow indicating that air may actually be flowing backwards in the outer portion of the impeller passage. Considerable difficulty was experienced in obtaining the necessary lighting to bring out

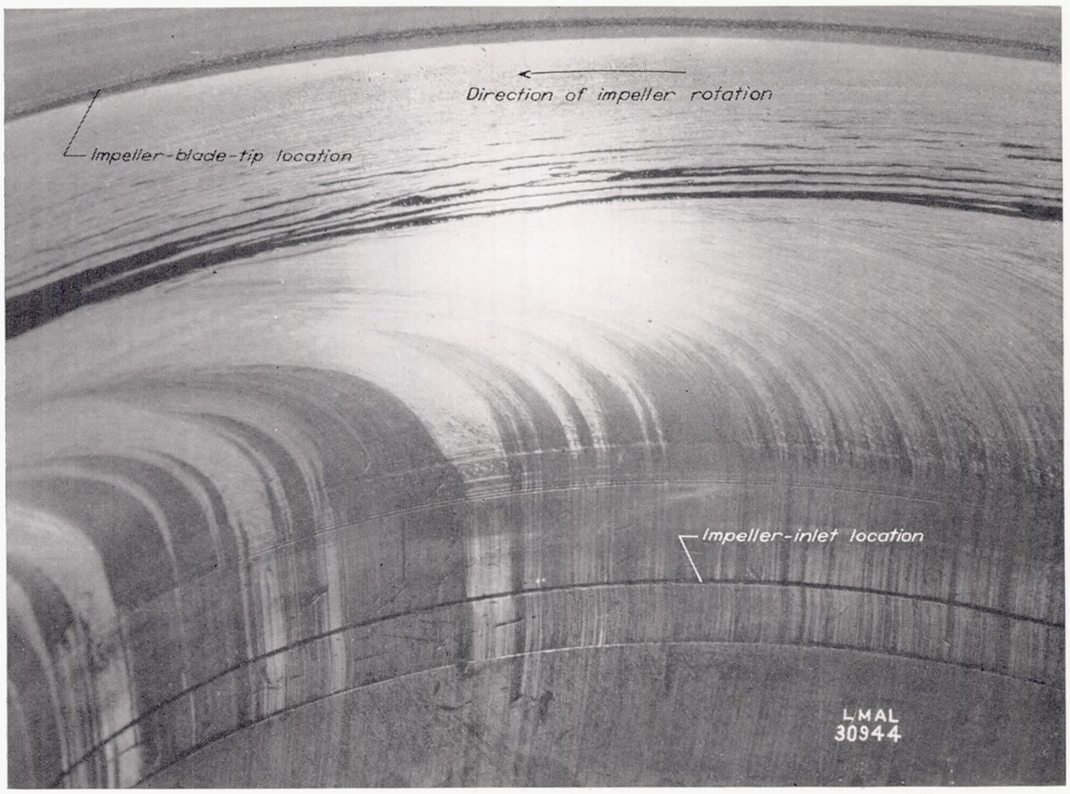


FIGURE 6.—Lampblack pattern on mixed-flow-type impeller front housing for Q/n value of 0.305. Run 1.

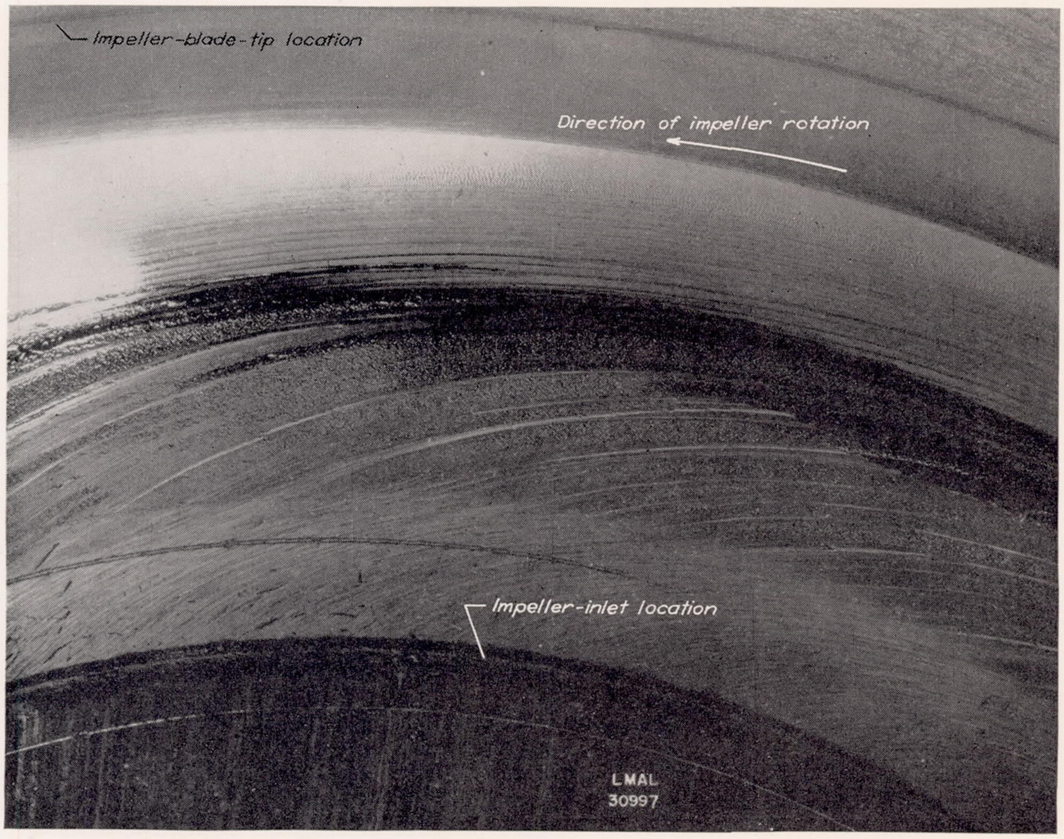


FIGURE 7.—Lampblack pattern on mixed-flow-type impeller front housing for Q/n value of 0.225. Run 2.

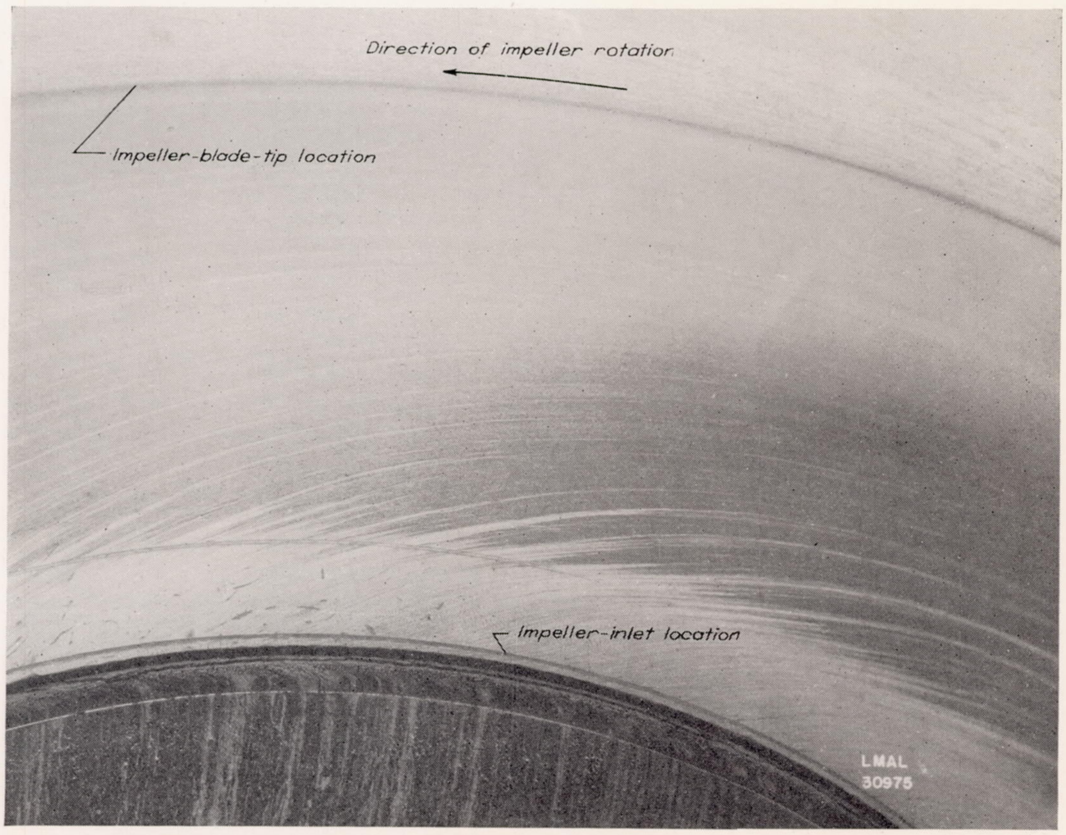


FIGURE 8.—Lampblack pattern on mixed-flow-type impeller front housing for Q/n value of 0.220. Run 3.

the desired points without having high lights appear on the photographs. Consequently, the outer one-third of the blades of the impeller on the left side of figure 10 appears to be nearly free of lampblack deposits because of direct light reflection from this portion of the impeller. The right side of the photograph gives a clearer picture of the true relation of the lampblack deposits.

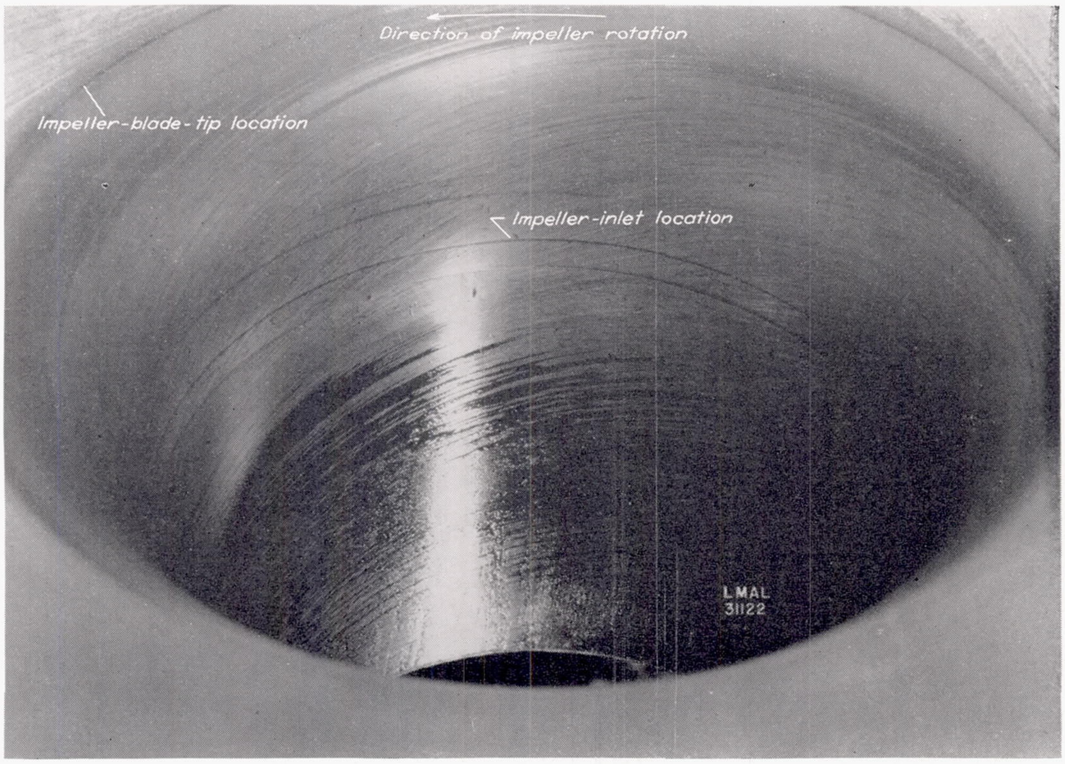


FIGURE 9.—Lampblack pattern on mixed-flow-type impeller front housing for Q/n value of 0.132. Run 4.

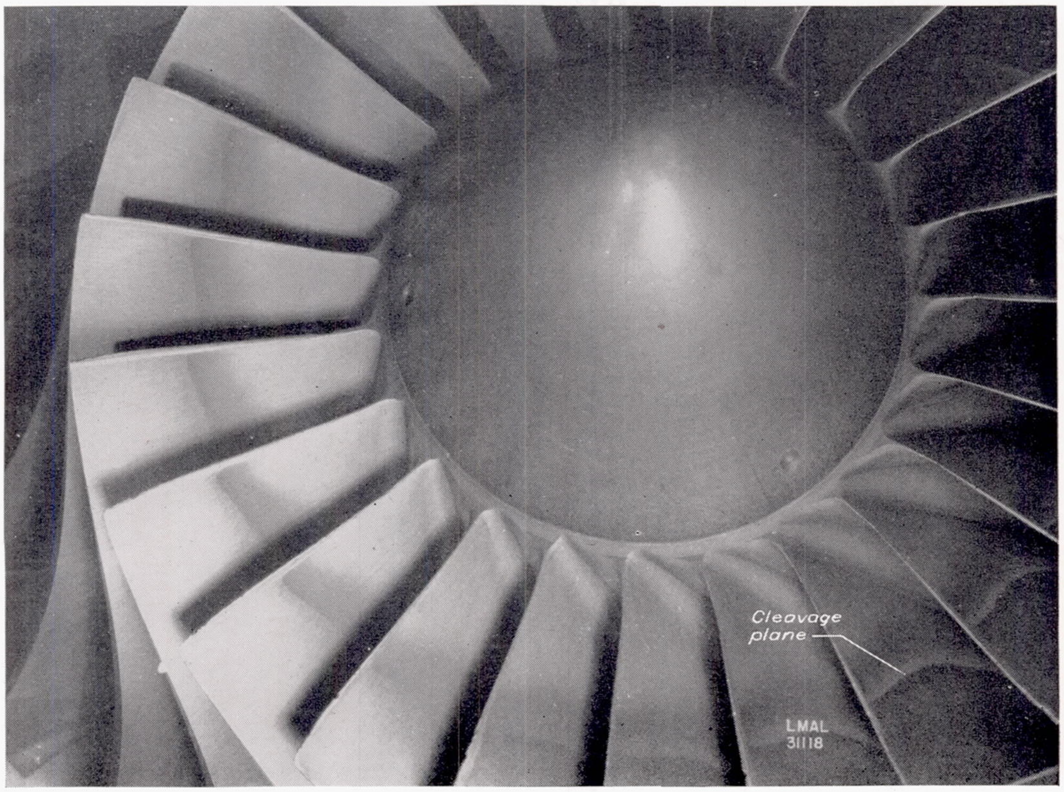


FIGURE 10.—Lampblack pattern on mixed-flow-type impeller for Q/n value of 0.132. Run 4.

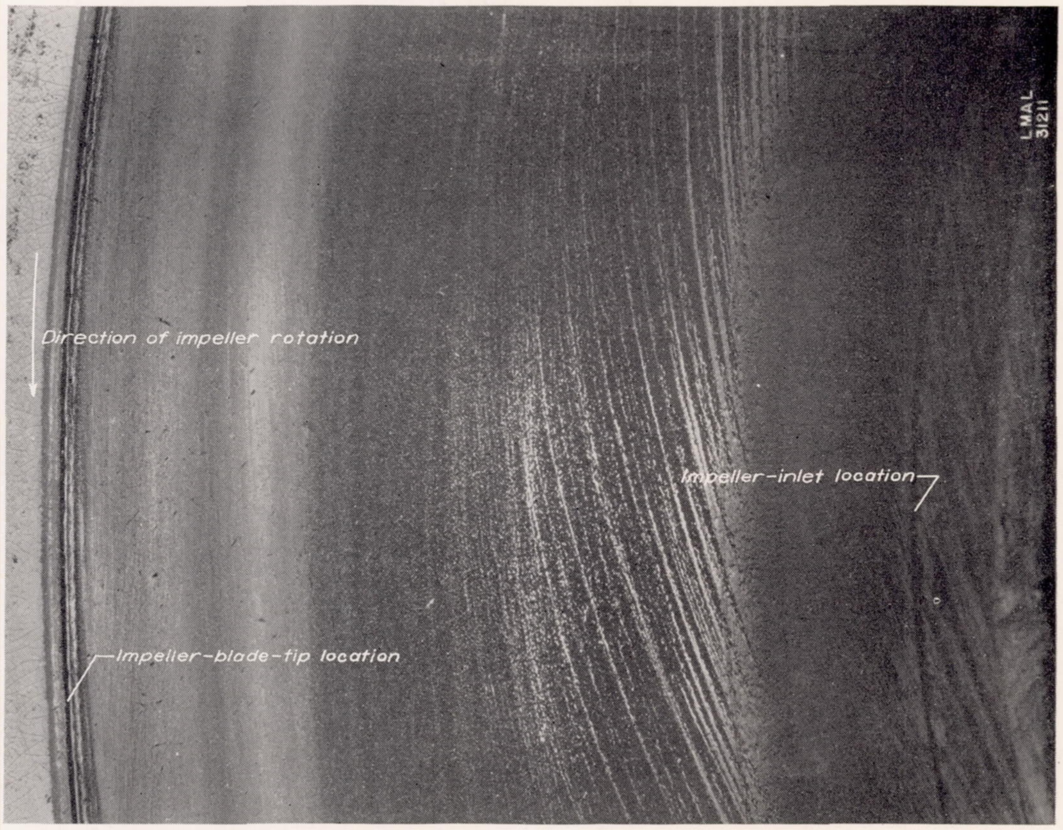


FIGURE 11.—Lampblack pattern on mixed-flow-type impeller front housing for Q/n value of 0.100. Run 5.

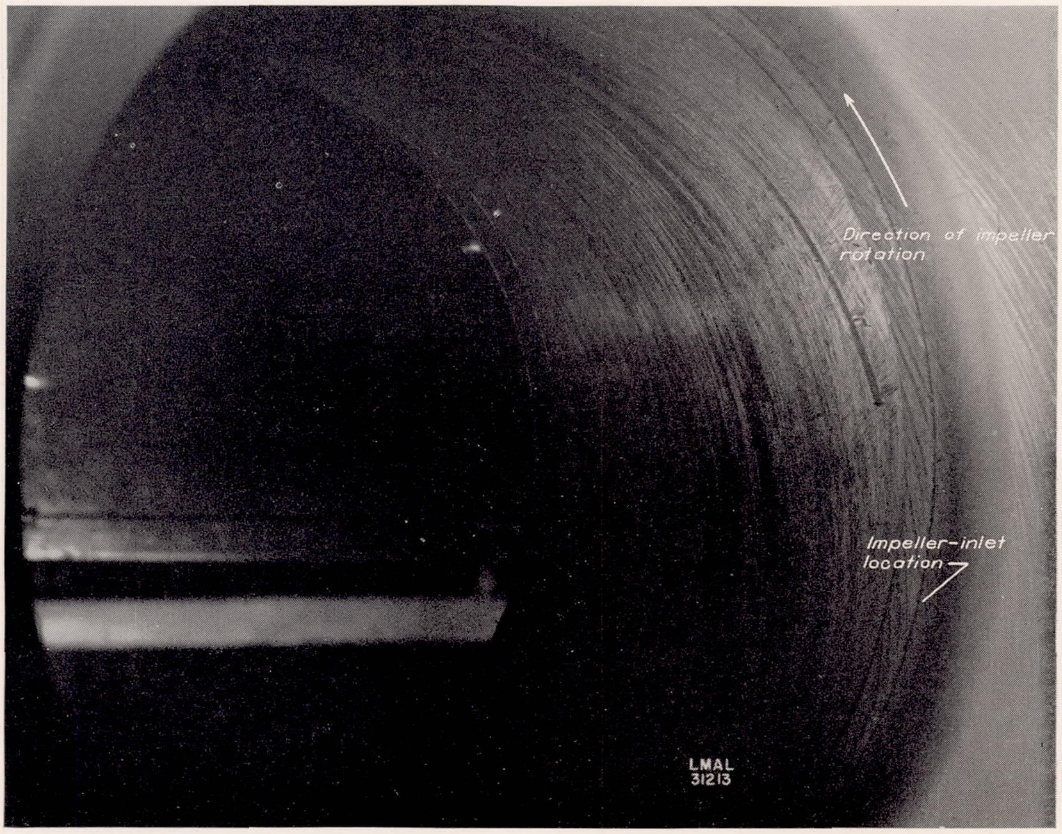


FIGURE 12.—Lampblack pattern on mixed-flow-type compressor inlet-pipe wall for Q/n value of 0.100. Run 5.

Photographs of the pattern obtained on the impeller front housing and on the inlet-pipe wall at a Q/n value of 0.100 (run 5) are shown in figures 11 and 12, respectively. At this very low value of Q/n, the backflow appeared to begin at the impeller-blade tip and extended several diameters up the inlet pipe. The pattern obtained on the impeller in this run was very indistinct due to the high degree of turbulence that existed at the impeller inlet and is not reproduced herein.

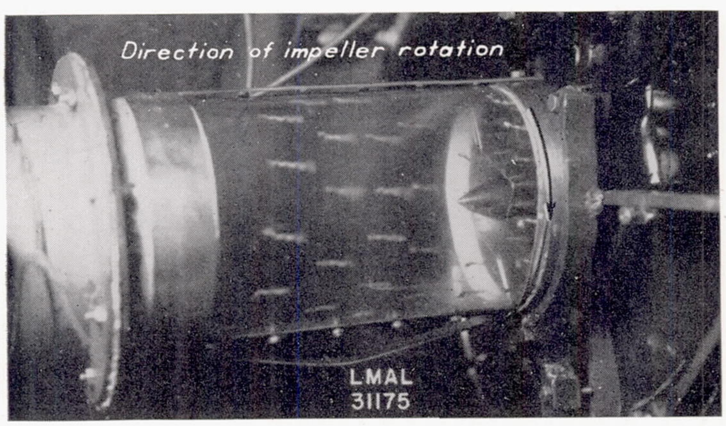
This series of lampblack patterns indicates that even at maximum Q/n values a small amount of backflow appears to exist near the blade tips on the impeller front housing. As the value of Q/n is decreased, the extent of this backflow increases until near the final surge point the backflow penetrates several diameters into the inlet pipe. There is also indication that this backflow extends into the impeller passage proper and is not confined to the clearance space between the impeller and the impeller front housing. These lampblack patterns gave an indication of the effect of backflow only on the boundary layer and not on the main body of the flow.

Tuft studies.—In the tuft studies made at the inlet of a conventional centrifugal compressor, the tufts were placed along the inside wall of the duct to obtain information on the penetration and the rotation of the backflow for various values of Q/n. Photographs of the attitude of the tufts taken while the compressor was operated at high, medium, low, and very low values of Q/n at a tip speed of 900 feet per second are shown in figure 13. At high values of Q/n (fig. 13 (a)), there is no evidence of backflow in the inlet pipe. For a medium value of Q/n, although the turbulence of the boundary layer has increased slightly, there is still no backflow (fig. 13 (b)). For a low value of Q/n, a definite backflow extends approximately 1 diameter up the inlet pipe (fig. 13 (c)). This backflow is indicated by the change in direction of the tufts near the impeller inlet. At very low values of Q/n (fig. 13 (d)), the backflow is much more severe and extends at least 2 diameters up the inlet pipe.

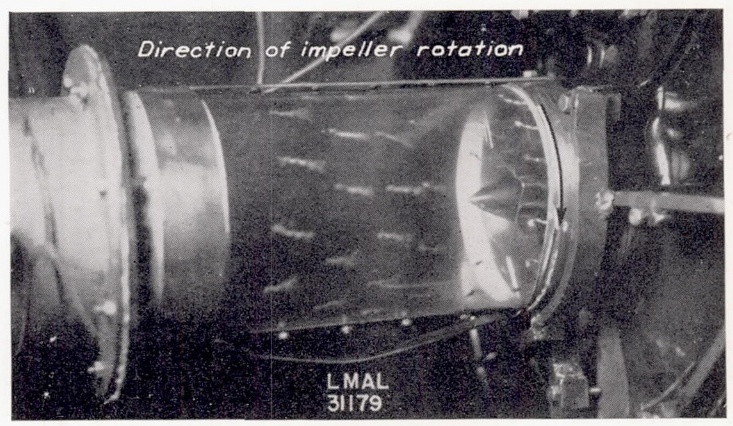
An indication of the effect on the main body of the flow was obtained by mounting tufts on two strings passed through the center of the pipe. Photographs were made of the attitude of these tufts while the compressor was operated at approximately the same values of Q/n as before. The results (fig. 14) show that, as the value of Q/n is decreased, the turbulence existing near the center of the duct continuously increases. At very low values of Q/n (fig. 14 (d)), there is a slight indication of prerotation but the random turbulence was so great that no definite trend could be noted.

BACKFLOW SURVEYS

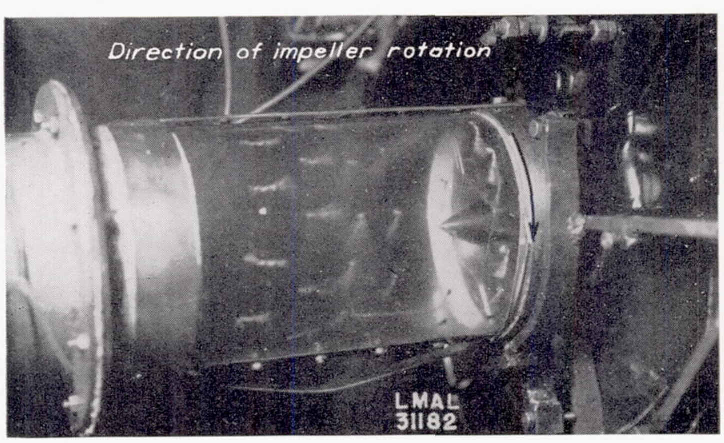
The three values of Q/n at which surveys were taken on the experimental compressor are indicated on the adiabatic-efficiency η_{ad} curve (fig. 15). Because it had been previously determined that no backflow existed at the impeller inlet at high values of Q/n, the first survey was taken near the point of maximum efficiency ($Q/n=0.0926$). The second survey



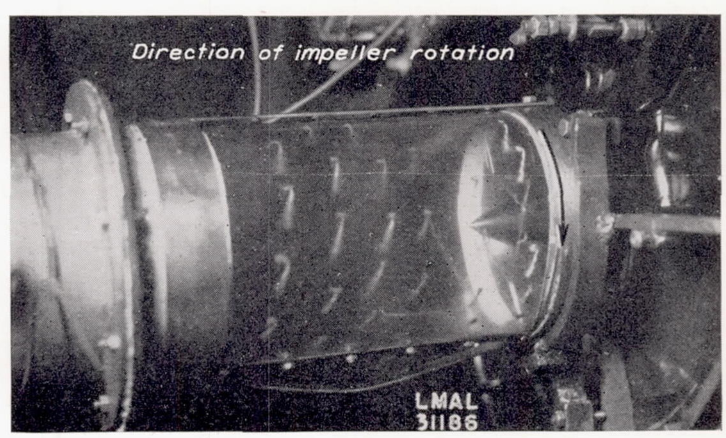
(a) High Q/n.



(b) Medium Q/n.

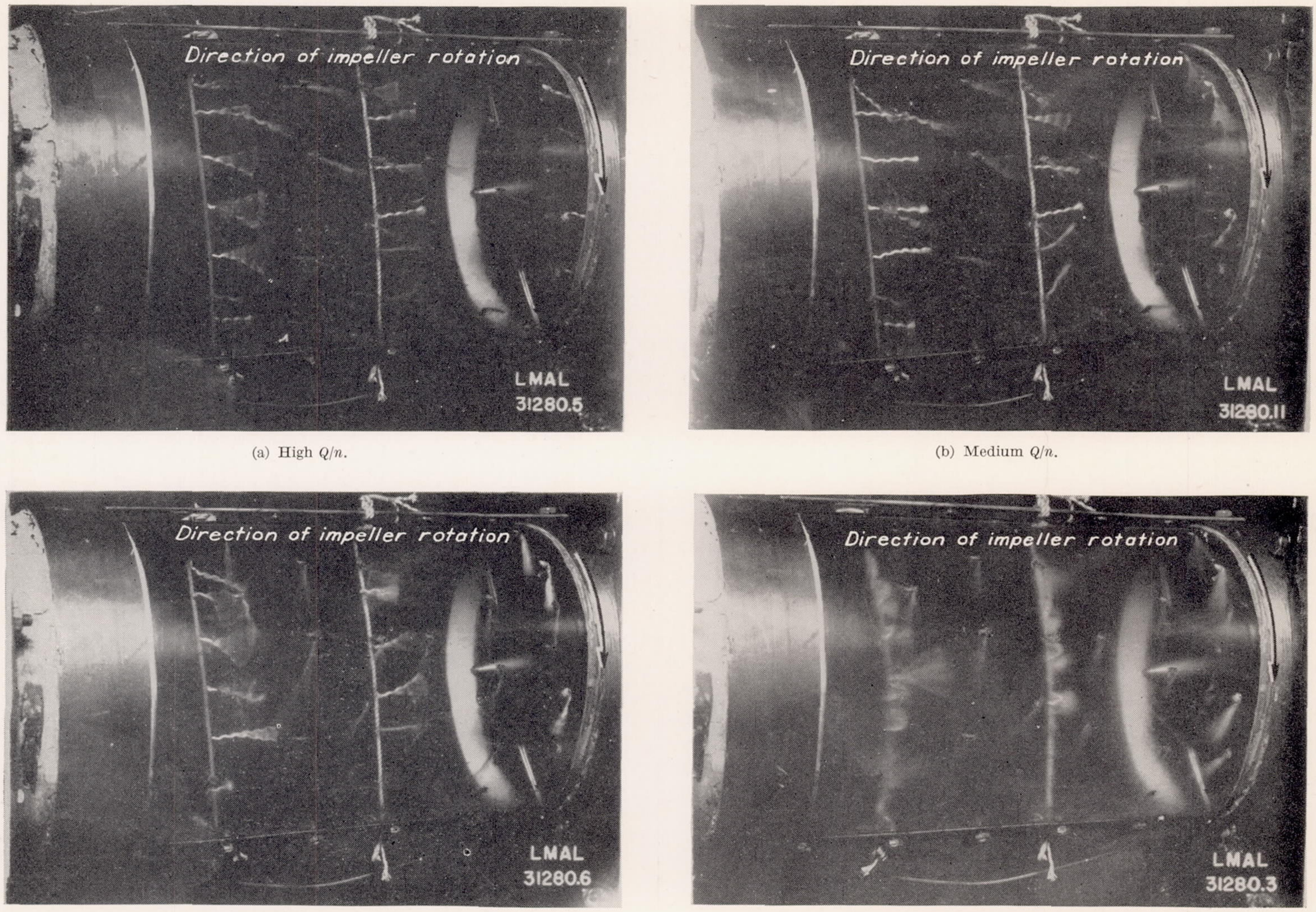


(c) Low Q/n.



(d) Very low Q/n.

FIGURE 13.—Tuft studies of boundary-layer flow in inlet pipe of conventional centrifugal compressor at a tip speed of 900 feet per second.



(a) High Q/n.

(b) Medium Q/n.

(c) Low Q/n.

(d) Very low Q/n.

FIGURE 14.—Tuft studies of main flow in inlet pipe of conventional centrifugal compressor.

was made at the point ($Q/n=0.0824$) where definite evidence of backflow was first noted, and the third survey was taken just above the surge point ($Q/n=0.0517$).

The angle of flow, measured by the Fechheimer tube, was the angle between the axial direction and the direction of flow and was measured in a plane normal to the survey. The flow angles θ obtained from these surveys are plotted against l/L, where l/L is the ratio of the radial distance of a particular point from the center line of the inlet pipe to the total radius of the inlet pipe at the survey station (fig. 16). For a Q/n value of 0.0926, the angle θ is slightly negative. This negative angle, although within the limits of accuracy of the angle measurements, may indicate a rotation of the incoming air in a direction opposite to that of the impeller and may be caused by an induced rotation from circulation around the impeller blades. At the Q/n value of 0.0824, the angle obtained is negative near the center of the inlet, zero at a radius ratio of 0.62, and then increases rapidly to a positive value of approximately 97° at the pipe wall. For an angle of 90°, the axial component of velocity is zero, whereas for values of θ greater than 90° the axial component of velocity is negative and represents backflow. At a Q/n value of 0.0517, the angle of flow at the inside of the passage is positive and increases to a value of 111° near the pipe wall. Backflow is shown between the radius ratios of 0.84 and 1.00. If the backflow in the compressor were confined to the clearance space between the impeller and the front housing, this flow would have to expand through an included angle of 68° to obtain these results at the survey station, which was only 0.19 inch from the impeller face. Inasmuch as the angle of expansion of free jets is in the order of 14°, the backflow must actually extend into the impeller passage. The fact that backflow is not limited to the clearance space is in agreement with the results of run 4

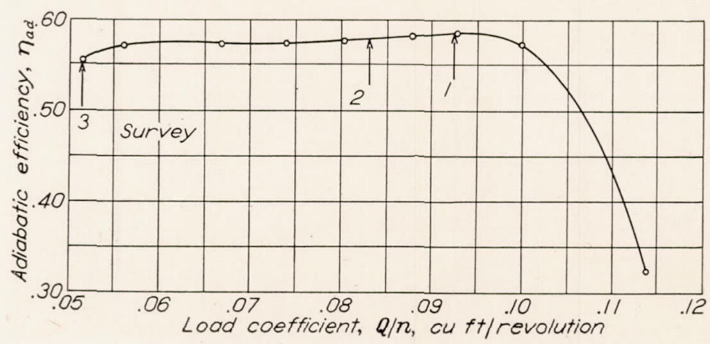


FIGURE 15.—Adiabatic efficiency of experimental compressor for actual impeller-tip speed of 1200 feet per second and outlet pressure of 10 inches of mercury above atmospheric. (Arrows indicate points where surveys were made.)

of the lampblack tests. (See fig. 10.) The positive angle near the spinner nut is due to a prerotation caused by the mixing of the backflow, which has a high degree of rotation, with the incoming air. From these surveys it can be seen that at high values of Q/n the flow is nearly axial. As the value of Q/n is decreased, however, the axial component of velocity becomes very small near the wall and a further decrease in Q/n causes a backflow and a relatively high degree of prerotation. The angle of flow represents only the ratio of tangential to axial velocity, and the magnitude of the resultant velocity must also be considered in determining the extent of prerotation and backflow.

A comparison of the axial components of velocity for these surveys is given in figure 17. For a Q/n value of 0.0926, the velocity profile is comparatively flat. Decreasing the value of Q/n to 0.0824 causes very little change in the magnitude of the velocity near the center of the inlet. Near the pipe wall, however, the velocity is very much lower and an actual reverse flow of air is indicated by the negative values beyond the radius ratio of 0.97. At a Q/n value of 0.0517, the axial velocity near the center of the inlet pipe is the same as in the two previous surveys, but the velocity is much lower in the outer portion of the inlet pipe and backflow is evidenced between the radius ratios of 0.84 and 1.00.

A comparison of the tangential components of velocity for these surveys is shown in figure 18. The velocities are plotted as the ratio of the tangential velocity of the air $V_{\theta,a}$ at a given radius to the tangential velocity of the impeller $V_{\theta,i}$ at the same radius, thus indicating the variation

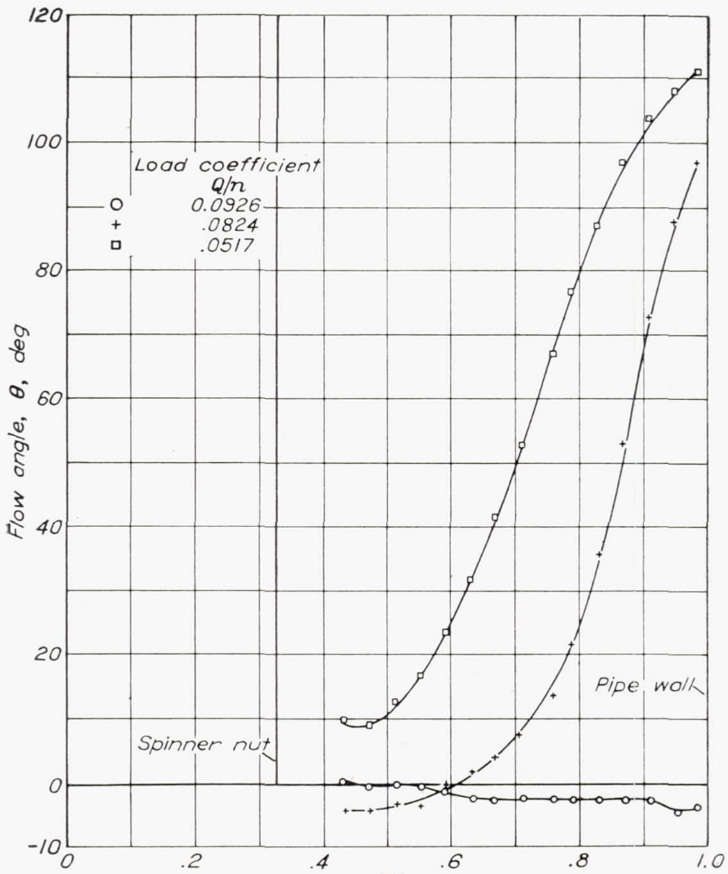


FIGURE 16.—Effect of various values of Q/n on angularity of flow at inlet of experimental compressor for actual impeller-tip speed of 1200 feet per second and outlet pressure of 10 inches mercury above atmospheric.

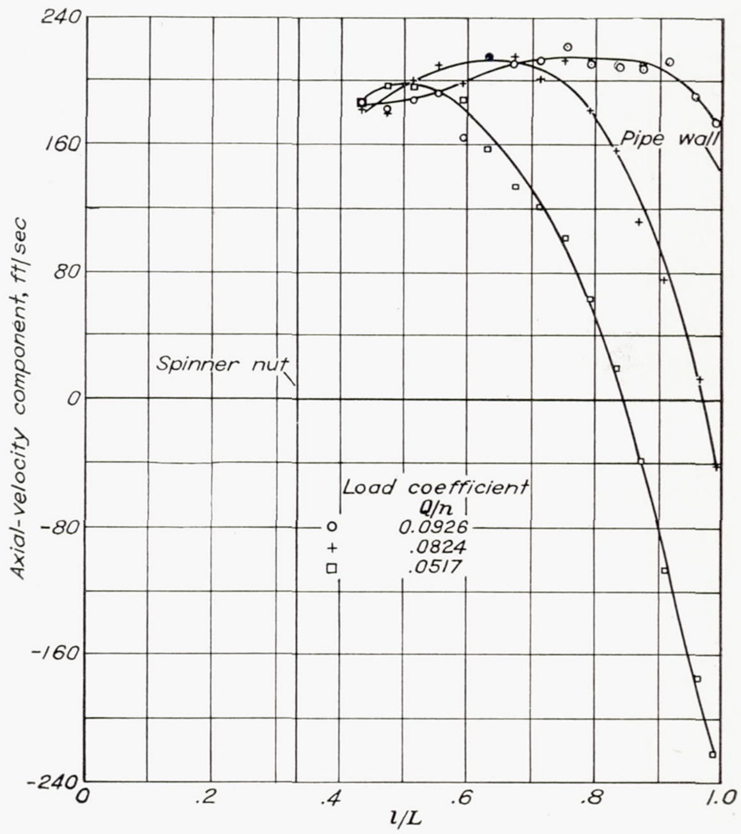


FIGURE 17.—Effect of various values of Q/n on axial-velocity components at inlet of experimental compressor for actual impeller-tip speed of 1200 feet per second and outlet pressure of 10 inches mercury above atmospheric.

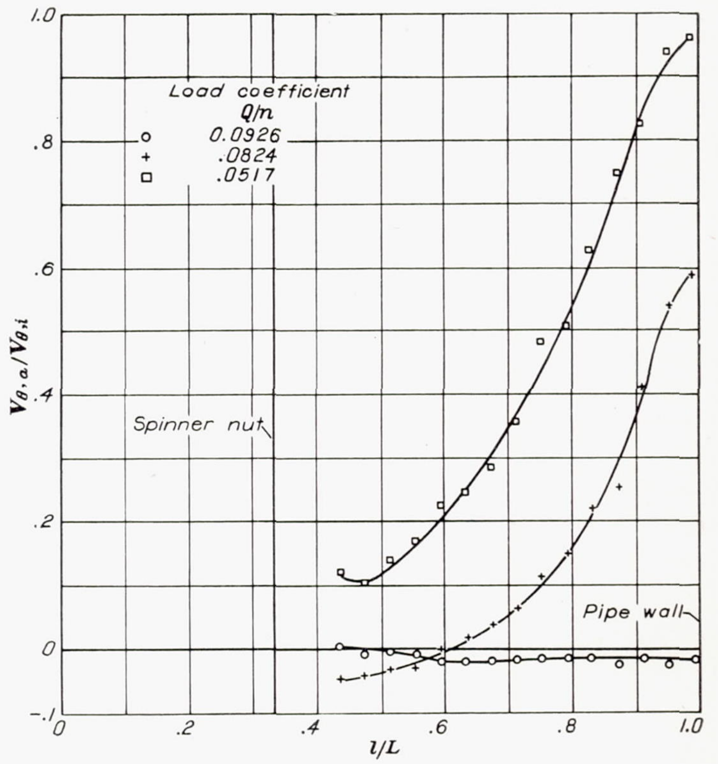


FIGURE 18.—Effect of various values of Q/n on tangential-velocity components at inlet of experimental compressor for actual impeller-tip speed of 1200 feet per second and outlet pressure of 10 inches mercury above atmospheric.

from a wheel-type rotation. Figure 18 shows that for high values of Q/n the prerotation is negligible. As the value of Q/n is decreased, however, the prerotation near the pipe wall approaches the rotational velocity of the impeller, becoming approximately 0.95 of the impeller velocity for a Q/n value of 0.0517. Negative values at a Q/n value of 0.0926 indicate that the rotation of the air is opposite to the rotation of the impeller.

For any impeller-tip speed, the angle of attack of the blades is a function of the axial component of velocity and the angularity of the flow. Near the center of the inlet pipe, the axial component of velocity and the angularity of the flow are practically independent of the value of Q/n at which the impeller is operating; therefore, the angle of attack of this portion of the blades is relatively constant regardless of the value of Q/n. The angle of attack of the blades in the outer portion of the inlet pipe will vary considerably with Q/n because the axial component of velocity and the angularity of flow change radically with changing values of Q/n. For high degrees of prerotation near the outer portion of the blades, however, the angle of attack may decrease.

The results of the temperature surveys, which were taken under the same conditions as the angle and velocity surveys, are presented in figure 19. These curves show the temperature rise between the orifice tank and the survey station plotted against radius ratio at the survey station. Even at the relatively high Q/n value of 0.0926 where no backflow occurred, a definite temperature gradient was observed at the impeller inlet. This increase in temperature near the wall is probably a result of heat transfer from the compressor housing through the inlet-pipe wall. At the lower values of Q/n, the increase in temperature gradient is due to the presence of backflow and its mixing with the incoming air. Some heat transfer probably always exists at the pipe wall; therefore, the temperature near the wall cannot be used as a measure of the intensity of the backflow. Near the spinner nut, negative values of temperature rise are obtained for the two high values of Q/n. Although these negative values are less than the limits of accuracy of the temperature-measuring device, the fact that they occur at both values of Q/n indicates that there is a temperature drop resulting from a velocity increase between the orifice tank and the survey station. At the lowest value of Q/n, the positive values of the temperature rise near the inside of the pipe can be due only to backflow. This conclusion is in agreement with the data for the tangential component of the velocity presented in figure 18 and shows that as Q/n decreases the increase in the amount of backflow results in a mixing action with a consequent increase in temperature and prerotation of the incoming air.

EFFECT OF MACH NUMBER AND REYNOLDS NUMBER ON BACKFLOW

In order to determine the effect of impeller-tip speed on the backflow characteristics, surveys similar to those previously presented were made for impeller-tip speeds of 960 and 1080 feet per second. Cross plots of the data thus obtained are presented in figures 20 and 21. The variation of the angle of flow with tip speed for several constant values of Q/n and for values of radius ratio of 0.60, 0.75, and 0.90 is shown in figure 20. Corresponding curves for the effect of tip speed

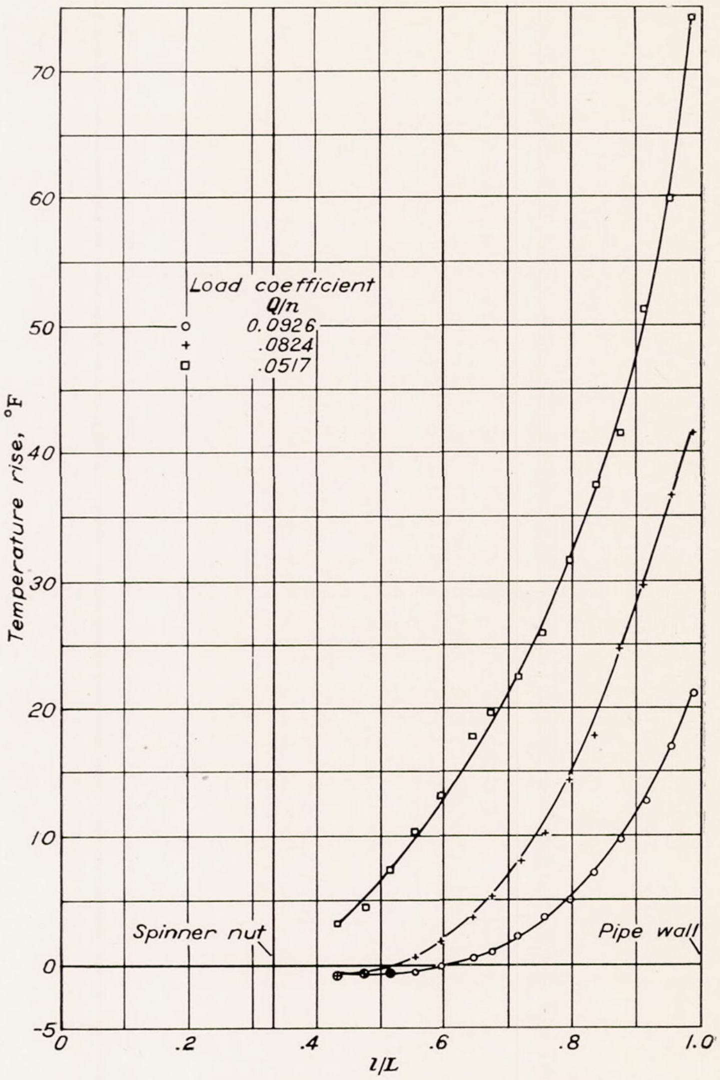


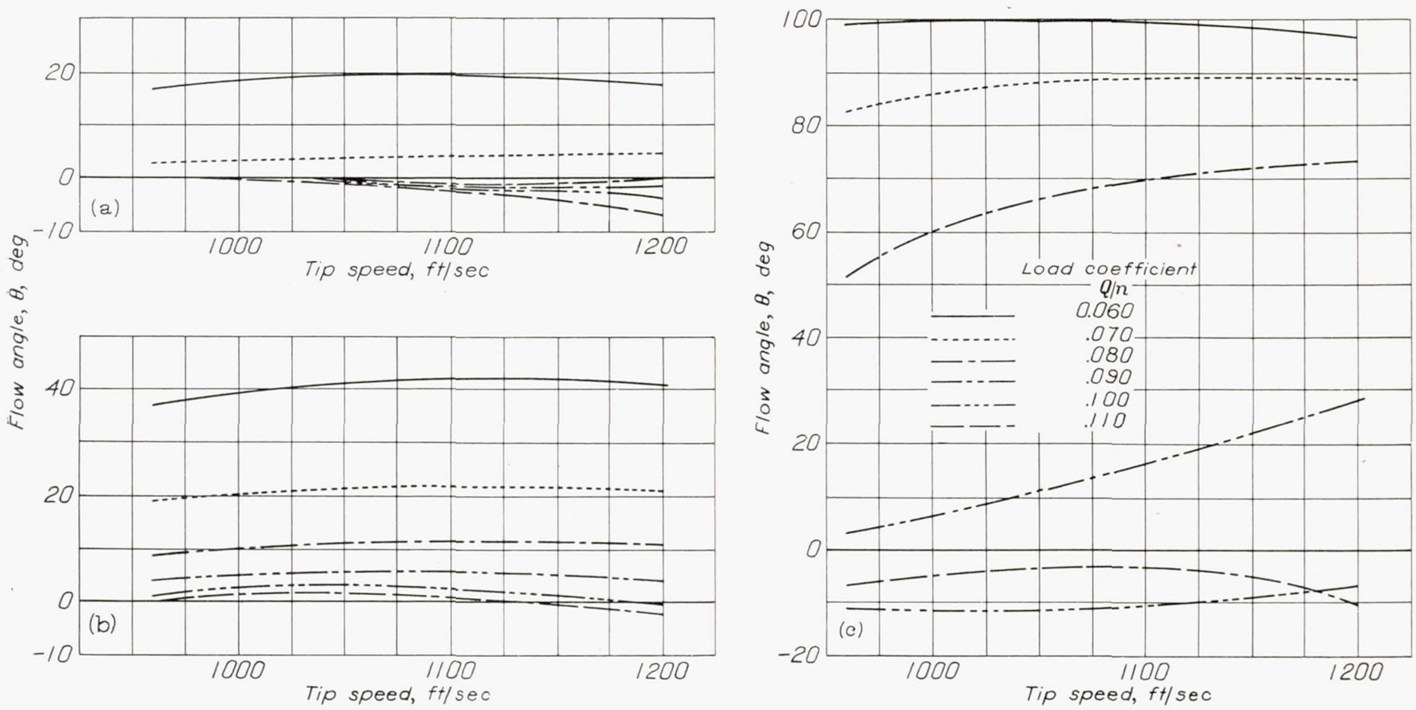
FIGURE 19.—Effect of various values of Q/n on temperature rise at inlet of experimental compressor for actual impeller-tip speed of 1200 feet per second and outlet pressure of 10 inches mercury above atmospheric.

on temperature rise are shown in figure 21. Inasmuch as the variation shown does not follow a definite trend with varying tip speed, no appreciable effect of Mach number and Reynolds number on the characteristics of backflow is indicated in the range of tip speeds investigated.

DISCUSSION OF RESULTS

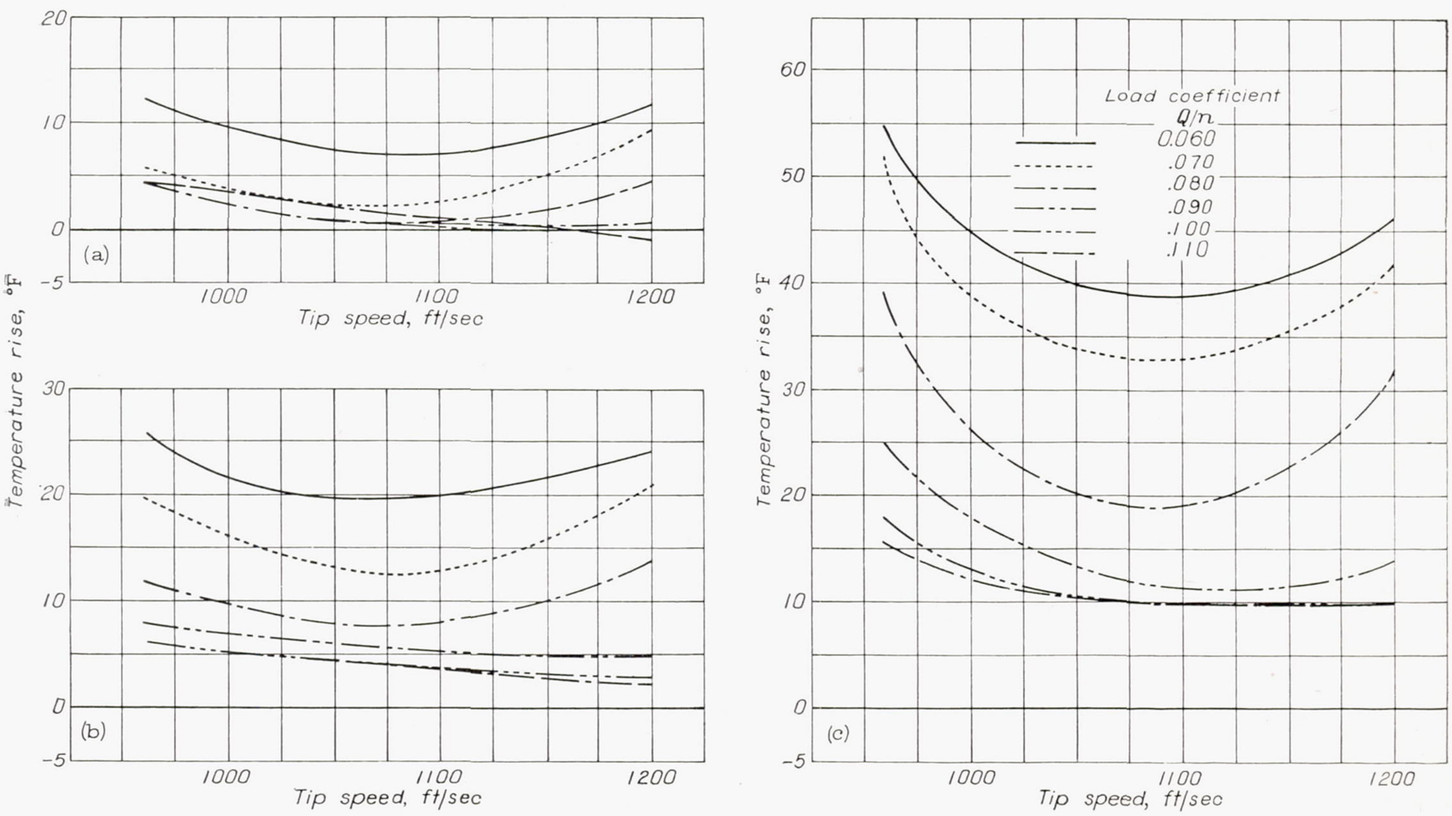
For conventional-type impellers operating at high values of Q/n, the rotational acceleration will cause a continually increasing pressure gradient near the inlet. On the other hand, the increasing curvature of the front housing will produce a pressure gradient that will oppose the gradient caused by rotational acceleration. A consideration of the flow area indicates that it will not contribute to the production of a favorable pressure gradient. At high values of Q/n, the momentum of the tangential component of relative velocity probably will be sufficient to overcome any resulting adverse pressure gradient and, if it is not, the added momentum of the axial component of velocity may contribute to the inhibition of backflow in the region of the impeller inlet.

A consideration of the flow near the impeller tip at high values of Q/n shows that an adverse pressure gradient may



(a) Radius ratio, 0.60.
(b) Radius ratio, 0.75.
(c) Radius ratio, 0.90.

FIGURE 20.—Effect of actual impeller-tip speed on angularity of flow for various values of Q/n.



(a) Radius ratio, 0.60.
(b) Radius ratio, 0.75.
(c) Radius ratio, 0.90.

FIGURE 21.—Effect of actual impeller-tip speed on temperature rise for various values of Q/n.

exist due to decreasing curvature of the front housing. Furthermore, the increasing density in this region together with a practically constant flow area causes a considerable adverse pressure gradient in addition to that created by the centrifugal force. This additional gradient must be balanced by the momentum of the air and, if this momentum is insufficient, a backflow will occur.

At low values of Q/n, if the incoming flow is purely axial, the rate of the rotational acceleration near the impeller inlet will tend to be much greater than for high values of Q/n because of the higher angle of attack of the blades with respect to the air and the resulting higher blade loading at the leading edges of the blades. As a result, a much more severe adverse pressure gradient will be developed because the rate of rotational acceleration in a given axial distance will be increased. In addition, the opposing effect due to increasing curvature will be less and the effect of area will still be adverse. Furthermore, the momentum resulting from the axial component of velocity will be much smaller for low than for high values of Q/n. These factors indicate that the tendency toward backflow in the region of the impeller inlet will be much greater for low than for high values of Q/n, this trend is in agreement with the results obtained. At low values of Q/n, the effects of the decreasing curvature of the front housing and the increasing density in the region of the blade tips will be approximately the same as for high values of Q/n. The magnitude of the backflow, however, is greater due to the reduced momentum of the incoming air. This conclusion is in agreement with the results of this investigation inasmuch as backflow in the region of the blade tips was indicated at all values of Q/n.

At a zero value of Q/n, the centrifugal pressure gradient would cause the pressure near the hub of the impeller inlet to be less than that in the inlet pipe, whereas that near the tip of the blades would be greater than that in the inlet pipe. This pressure distribution causes a circulating flow, which enters the impeller near the hub and is discharged into the inlet pipe from the outer portions of the impeller annulus. The axial velocity distribution observed at low values of Q/n may be regarded as an extension of this trend.

SUMMARY OF RESULTS

From an investigation of compressors with axial inlets, the following results were obtained. Caution must be exercised, however, in applying the results of this investigation to actual compressor installations in which the inlets are of a different nature.

1. At high values of load coefficient, any backflow that existed was confined to a region near the impeller-blade tips. As the value of load coefficient was decreased, however, this region of backflow extended backward along the impeller front housing until, at very low values of load coefficient, the backflow penetrated several diameters into the inlet pipe.

2. The value of load coefficient was the determining factor of the backflow characteristics; the effect of Reynolds number and Mach number was negligible.

3. At very low values of load coefficient, the backflow actually extended into the impeller passage and was not confined to the clearance space between the impeller blades and the impeller front housing.

4. The axial component of velocity near the center of the impeller-inlet pipe did not appreciably change with load coefficient.

5. The mixing of the heated backflow air caused a definite increase in the inlet-air temperature and a very large radial temperature gradient at the impeller-inlet annulus.

6. The backflow resulted in a high degree of turbulence and a definite prerotation in the inlet pipe at the impeller entrance. Although the degree of prerotation near the center of the pipe was not appreciable, that near the inlet-pipe wall had approximately the same magnitude as the impeller rotation.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, *June 1, 1945*.

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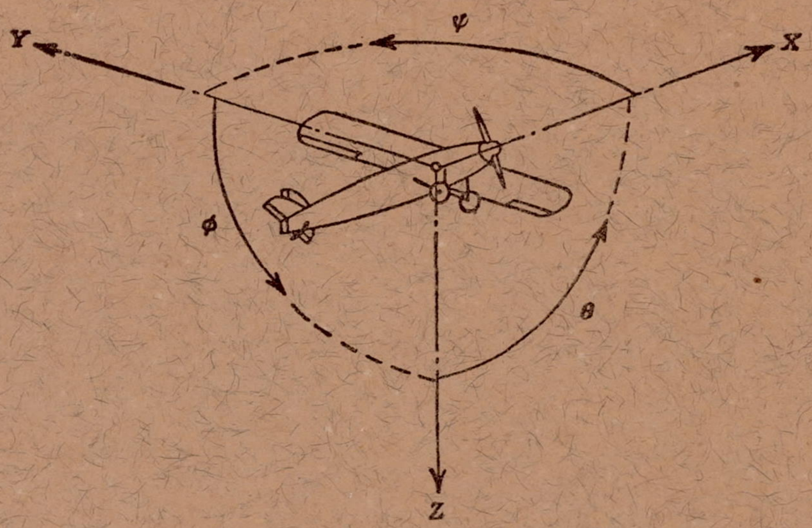

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis: Designation	Axis: Symbol	Force (parallel to axis) symbol	Moment about axis: Designation	Moment about axis: Symbol	Moment about axis: Positive direction	Angle: Designation	Angle: Symbol	Velocities: Linear (component along axis)	Velocities: Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l=\frac{L}{qbS}$ (rolling) $C_m=\frac{M}{qcS}$ (pitching) $C_n=\frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D	Diameter	
p	Geometric pitch	
p/D	Pitch ratio	
V'	Inflow velocity	
V_s	Slipstream velocity	
T	Thrust, absolute coefficient $C_T=\frac{T}{\rho n^2 D^4}$	
Q	Torque, absolute coefficient $C_Q=\frac{Q}{\rho n^2 D^5}$	
P	Power, absolute coefficient $C_P=\frac{P}{\rho n^3 D^5}$	
C_s	Speed-power coefficient $=\sqrt[5]{\frac{\rho V^5}{P n^2}}$	
η	Efficiency	
n	Revolutions per second, rps	
Φ	Effective helix angle $=\tan^{-1}\left(\frac{V}{2\pi r n}\right)$	

5. NUMERICAL RELATIONS

1 hp=76.04 kg-m/s=550 ft-lb/sec
1 metric horsepower=0.9863 hp
1 mph=0.4470 mps
1 mps=2.2369 mph

1 lb=0.4536 kg
1 kg=2.2046 lb
1 mi=1,609.35 m=5,280 ft
1 m=3.2808 ft