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Summary

An operational checkout and shakedown of a new active sidewall-boundary-layer removal system, installed in 1984, was conducted in the Langley 0.3-Meter Transonic Cryogenic Tunnel. Prior to the installation of the active removal system, the sidewall-boundary-layer removal was done in a passive mode by exhausting directly to the atmosphere (i.e., no reinjection). With the active removal system, using a cryogenic compressor for reinjection, the removal capability was significantly increased at the low Mach numbers. Details of the active removal system are presented including the compressor reinjection circuit, the compressor pressure ratio/surge control, and the compressor recirculation loop. The control logic and features of the compressor surge control are explained. Limited performance tests of the active system showed a maximum mass flow removal rate of about 5 percent of the test section mass flow at a Mach number of 0.40 (compared with 0.25 percent with the passive system). At a near transonic Mach number of 0.73, the active system removed 2.50 percent of the test section mass flow compared with 1.85 percent removed with the passive system. Measured performance characteristics of the compressor over a wide range of stagnation pressures and temperatures are presented.

Introduction

Airfoil data obtained in two-dimensional wind tunnels are known to be influenced by wall interference effects. In particular, the interference of the sidewall boundary layers at transonic Mach numbers can be quite significant, as demonstrated by the ONERA (ref. 1) test on airfoils for different sidewall-boundary-layer thicknesses. In an effort to minimize the sidewall-boundary-layer interference, several modern airfoil test facilities employ some type of system for sidewall boundary-layer control. These systems are usually either a sidewall-boundary-layer removal system (refs. 2 and 3), which reduces the sidewall-boundary-layer thickness and energizes the boundary layer to reduce possible separation of the sidewall and model boundary layers, or a sidewall blowing system (refs. 4 and 5), which also energizes the sidewall boundary layer in order to prevent separation of the sidewall and model boundary layers. At the Langley Research Center, the need to minimize the influence of the sidewall boundary layer was recognized in the early design stages of the Langley 0.3-Meter Transonic Cryogenic Tunnel (0.3-m TCT), and plans were made to incorporate a sidewall-boundary-layer removal system. The plans were carried out in two successive phases of installation of the boundary-layer removal hardware. When the first phase was completed in 1981, the boundary-layer removal system was operational in the passive mode and some validation tests with airfoils were made (refs. 6 to 9). In the passive mode of boundary-layer removal, the amount of mass removed from the sidewall boundary layer is limited to the quantity of the liquid nitrogen LN_2 injected to maintain the mass and thermal balance requirements in the tunnel under a steady-state operating condition. In this mode of operation the amount of mass removal is significantly limited at low Mach numbers. However, if the mass removed from the sidewall boundary layer is reinjected into the wind tunnel, the steady-state mass and thermal balance requirements can be maintained under all conditions and the removal capability is greatly enhanced. In the 1984 completion of the second phase of installation, the ability to reinject the mass removed from the sidewall boundary layer back into the 0.3-m TCT circuit was incorporated by using a recirculation system (referred to as the active system) consisting of a cryogenic centrifugal compressor and the associated control systems. The active system significantly expands the sidewall-boundary-layer removal capabilities at the low to mid subsonic Mach numbers, a testing region over which the passive system cannot reduce the sidewall-boundary-layer thickness because it has virtually no removal capability at those Mach numbers. The combined capabilities of the active and passive systems provide sidewall boundary-layer removal rates that will significantly reduce the sidewall-boundary-layer displacement thickness at low subsonic to high transonic Mach numbers. In October 1984, a limited test program was conducted to check out the integration of the active removal system with the standard tunnel operation. The tests also established the performance limits of the active system cryogenic boundary-layer removal compressor over a wide range of stagnation pressures and temperatures while at the same time providing limited performance data of the active system at a subsonic and a transonic Mach number. The purpose of this paper is to present some salient features of the active removal system hardware, the associated system controls, and some results obtained during the combined performance tests of the cryogenic compressor operational validation and the sidewall-boundary-layer removal capability with the active system.

Nomenclature

ACFM	actual cubic feet per minute (reduced to a compressor inlet condition)

BL	boundary layer
b	span of tunnel
DV	digital valve
GN_2	gaseous nitrogen
hp	horsepower
IV	isolation valve
LN_2	liquid nitrogen
M	Mach number
$\dot{m}$	mass flow rate
n	speed of compressor drive motor, rpm
PR	compressor total-head pressure ratio, p_{dis}/p_{in}
p	pressure
R	unit Reynolds number, per foot
T	temperature
VV	vent valve
δ^*	sidewall-boundary-layer displacement thickness

Subscripts:

bl	boundary-layer removal
dis	discharge of compressor
in	inlet condition (compressor or digital valve)
j	junction of digital valves discharge
t	total condition in tunnel
ts	test section
∞	test section condition far upstream of perforated plates

Apparatus

0.3-m Transonic Cryogenic Tunnel

The Langley 0.3-m TCT is a continuous flow fan-driven transonic tunnel which uses cryogenic nitrogen as a test gas (ref. 10). It is capable of operating at Mach numbers up to about 0.9. The stagnation pressure and temperature can be varied from about 1.2 to about 6.0 atm and from 144°R to 576°R, respectively. Under steady operating conditions, the heat of compression imparted to the test gas by the fan is removed by automatic injection of liquid nitrogen into the tunnel circuit, and the stagnation pressure is maintained by the automatic control of the gaseous nitrogen exhaust.

Boundary-Layer Removal System

A sketch of the 0.3-m TCT with the boundary-layer removal system is shown in figure 1. The removal system can be operated in either the passive or the active mode by opening and closing the appropriate valves. In both modes the boundary-layer mass removed from the two sidewall boundary layers is independently controlled by digital valves on the discharge side of each sidewall. In the passive mode, with the vent valve opened and the isolation valve closed, the discharge from each wall is exhausted directly to the atmosphere. This mode of operation was employed in earlier tests (refs. 6 to 9) and has the limitation that the test section static pressure must be higher than the ambient pressure when it is used. Furthermore, in the passive mode, the maximum rate at which mass can be removed is limited to the rate at which liquid nitrogen is being injected into the tunnel in order to maintain steady operating conditions. At higher Mach numbers, the heat of compression is large; therefore, the liquid nitrogen injection rate will be higher and correspondingly higher removal rates can be obtained.

Because the passive sidewall-boundary-layer removal capability is not large enough to significantly reduce the sidewall-boundary-layer displacement thickness at the low to mid subsonic Mach numbers, the passive mode of operation is limited to the higher Mach numbers in the transonic range. At transonic Mach numbers, the passive system provides sufficient sidewall-boundary-layer removal to reduce the sidewall-boundary-layer parameter $2\delta^*/b$ by about 50 percent. With the active removal system available for operation, the boundary-layer removal rates are sufficiently large to adequately reduce $2\delta^*/b$ under all tunnel operating conditions. To switch over to the active mode of operation, the vent valve (fig. 1) is closed and the isolation valve opened, thus allowing the mass removed from the sidewall boundary layers to be processed by the compressor and reinjected into the tunnel circuit at the diffuser.

Test Section and Perforated Plates

A typical top view of the test section of the 0.3-m TCT is shown in figure 2. In this photograph, the top of the plenum chamber and the top slotted wall of the test section have been removed. Visible in the photograph are the airfoil model, boundary-layer removal ducting, and one of the two perforated plates. The perforated plates are fitted flush on both the sidewalls, upstream of the model location, to remove the sidewall boundary layer. The two-dimensional test section insert for this tunnel has a cross section of 8 by 24 in. which is surrounded by a rectangular plenum. The top and bottom walls of the test section have two slots each. The slots, which were designed with the low blockage criteria of reference 11, have a total open ratio of 5 percent for both the top and bottom walls.

The perforated plates currently in use have a nominal porosity of about 10 percent. The holes, which are electron beam drilled, have a nominal diameter of 0.005 in. and a spacing of 0.014 in. and have a slight divergence in the suction direction to improve pressure recovery. The surfaces of the perforated plates are etched and polished to obtain a smooth "flow surface" (about 15 microinches rms). This surface preparation and fabrication technique ensured that there was no appreciable thickening of the boundary layer over the perforated plate compared with that over the more frequently used solid walls. The finding that the boundary-layer growth over the perforated plate is approximately the same as that over a solid plate is based on calculations and measurements described in reference 6. The perforated plates are mounted on a honeycomb backing (see fig. 3) using an adhesive bond to provide adequate strength to withstand the operating loads.

Active Removal System

A schematic of the boundary-layer removal system is shown in figure 4. The gas that is removed from the sidewall boundary layer leaves the digital valves and is compressed by the centrifugal compressor to provide sufficient pressure for reinjection into the tunnel circuit at the high-speed diffuser at four locations. (See fig. 1.) The pressure ratio across the compressor ranges from about 2.1 to 2.4 depending on the inlet pressure and temperature of the gas entering the compressor. For sufficiently high mass-flow removal rates from the test section, the compressor discharge is directly reinjected into the diffuser. At lower removal rates, when the flow rate into the compressor drops to a low level, the compressor can go into an unstable operating condition referred to as surge. If the compressor goes into surge, it is automatically corrected by the opening of the recirculation-surge flow control valves, with additional mass supplied by the injection of LN_2 into the recirculation loop. (See fig. 4.) When these valves are opened, there is a higher mass flow through the compressor which takes the compressor out of surge. The two recirculation-surge flow control valves also help to maintain the proper pressure ratio across the compressor.

The temperature at the inlet to the compressor is controlled by the injection of LN_2 into the piping well upstream of the compressor inlet. The vent valve on the discharge side of the compressor is used to relieve the line pressure if it exceeds 90 psia. The entire discharge from the compressor can be diverted into the recirculation loop (prior to reinjection into the diffuser) by closing an isolation valve.

Digital Valves

The precise control of the rate of sidewall-boundary-layer removal by the system (see fig. 4) is possible with the two digital valves and their associated controls. Each digital valve consists of a number of calibrated sonic nozzles operating in a bistable mode either open or closed. The sonic nozzles are used in appropriate combinations to give the required flow area. The 11-bit digital valve used in the present system has a resolution of 1 in 2048 and is microprocessor controlled. The microprocessor maintains a constant mass removal rate through the perforated plates at a level specified by command set points. Each of the digital valves can be driven to a command set point by a feedback control loop which sets the mass flow through the perforated plates in terms of either actual rate of flow or percent of the test section mass flow. The desired mass removal rate is set on the control panel thumbwheel for input to the microprocessor. The tunnel total pressure, static pressure, and total temperature are input to the microprocessor to determine the test section mass flow rate. (See fig. 5.) The mass flow rate through the digital valves is determined by the microprocessor from an input of the inlet total pressure and temperature from each of the two digital valves. The pressure at the junction of the two discharge lines from the digital valves is also input to the microprocessor to make sure there is enough pressure drop (at least 15 percent) across the digital valve to have sonic flows through the nozzle elements. A fault light on the control panel indicates when there is less than a 15-percent pressure drop across either of the digital valves.

The installation of the two digital valves is shown in figure 6. They are located on the roof of the building containing the 0.3-m TCT and are in an enclosure to protect them from the weather. A piping duct from each side of the test section enters the bottom of the digital valves and the discharge ducts to the compressor are on the side of the valves. The photograph also shows the exhaust line to the atmosphere and the vent valve, which is open for passive operation and closed for active operation.

Compressor

Pressure Ratio/Surge Control

One of the unique control features of the cryogenic centrifugal compressor used in the active system is that it is designed to operate at a constant pressure ratio of 2.15 (below an inlet temperature of 410°R). This type of control, at a constant pressure ratio, was selected because of the difficulty in having a conventional surge control system on a compressor that was designed to operate over a wide range of tunnel stagnation conditions (1.0 atm $\leq p_t \leq$ 6.0 atm and saturation temperature $\leq T_t \leq$ ambient). Therefore, it was decided to let the control of the pressure ratio also serve as surge control. This dual type of control (surge and pressure ratio) is possible since the design pressure ratio of the compressor at low flow rates (near surge) is about 2.33 and at the highest flow rates is near the set point value of 2.15. Thus, the pressure ratio controller (over most operating conditions) tries to achieve the lower pressure ratio of 2.15 by opening the recirculation valves and introducing a higher flow rate through the compressor. The process that regulates the pressure ratio toward 2.15 always takes the compressor away from a condition of surge. The pressure ratio controller that activates the recirculation loop valve is located in the compressor control panel. The control process of the compressor pressure ratio PR is based on the monitoring of the temperature at the inlet to the compressor and the use of this inlet temperature to prescribe a set point pressure ratio. (See fig. 5.) The following equations, which assume an ideal gas, are used in the pressure ratio controller to determine the set point pressure ratio:

$$\mathrm{PR} = p_{\mathrm{dis}}/p_{\mathrm{in}} = 2.15 \qquad (T_{\mathrm{in}} \leq 410^\circ\mathrm{R}) \quad (1)$$

$$\mathrm{PR} = p_{\mathrm{dis}}/p_{\mathrm{in}} = [(100.2/T_{\mathrm{in}}) + 1]^{3.5} \qquad (T_{\mathrm{in}} > 410^\circ\mathrm{R}) \quad (2)$$

The measured inlet and discharge pressures p_{in} and p_{dis} (i.e., measured pressure ratio) are input to the pressure ratio controller and compared with the set point pressure ratio calculated from equations (1) and (2). If the measured pressure ratio is greater than the set point value, the pressure ratio controller sends a signal to the recirculation valve actuators to open the recirculation loop valves to establish flow in the loop. The flow through the recirculation loop increases the mass flow into the compressor which, based on design (and later measured) compressor performance, drops the pressure ratio toward the set point value.

Motor Speed Control

The motor speed control (see fig. 5) is processed by the same microprocessor that controls the digital valves. The speed of the compressor motor n, which is directly related to the compressor pressure ratio, is based on the measured inlet temperature T_{in} of the compressor and is calculated from

$$n = 107.7\sqrt{T_{\mathrm{in}}}\ \mathrm{rpm} \qquad (T_{\mathrm{in}} \leq 410^\circ\mathrm{R}) \quad (3)$$

$$n = 2180\ \mathrm{rpm} \qquad (T_{\mathrm{in}} > 410^\circ\mathrm{R}) \quad (4)$$

A signal from the microprocessor is sent to the motor speed controller to maintain a speed based on the compressor inlet temperature and equations (3) and (4).

Inlet Temperature Control

The control of the compressor inlet temperature (see fig. 5) is done in the same microprocessor that controls the digital valves. The temperature controller compares the compressor inlet temperature with the tunnel total temperature and establishes a set point inlet temperature that is 36°R below the tunnel total temperature. When the actual inlet temperature is above the set point temperature, the temperature controller injects LN_2 upstream of the inlet to the compressor. (See fig. 4.) The injection of LN_2 is regulated by a feedback control loop in the temperature controller that drives the inlet temperature toward the set point temperature.

Drive System

A photograph of the compressor drive system consisting of the compressor, the gearbox, the drive motor, and the control panel is shown in figure 7. The compressor is driven by a 1000-hp variable-frequency motor through a gearbox which has a 9.2:1.0 gear ratio. Dry gaseous nitrogen GN_2 is continuously supplied to the buffered labyrinth seal between the gearbox and the compressor housing. The dry GN_2 seal gas prevents any moist air from entering the impeller cavity when the compressor is operating at subatmospheric conditions. The compressor casing is made of type 316 stainless steel and the impeller is made from an aluminum alloy suitable for cryogenic operation.

Results and Discussion

Sidewall-Boundary-Layer Removal System Performance Validation

The measured performance of the passive sidewall-boundary-layer removal system at unit Reynolds numbers of 20 × 10^6, 30 × 10^6, and 60 × 10^6 ft^{-1} is shown in figure 8(a) with the amount of removal presented in percent of the test section mass flow as a function of the test section Mach number. The data shown in figure 8(a) for the passive system represent about the maximum percent removal that can be obtained for a given Mach number and Reynolds number with this mode of sidewall-boundary-layer removal. The passive boundary-layer removal has an upper limit which ranges from about 0.25 percent at $M_\infty = 0.3$ to about 2.20 percent at $M_\infty = 0.9$. The solid lines represent fairing of the data and the dashed lines represent extrapolation of the data at a constant Reynolds number. The upper boundary of the passive removal capability has been established from previous tests (see refs. 6 to 9) and, as shown in figure 8(a), is slightly higher at the lower Reynolds number associated with warm operation and somewhat lower at the higher Reynolds numbers associated with cold conditions. For example, at a Mach number of about 0.73 a decrease in Reynolds number from 60 × 10^6 ft^{-1} to 20 × 10^6 ft^{-1} results in an increase in the removal capability from slightly less than 1.3 percent to about 1.9 percent. It is also shown that the passive removal capability significantly increases with increasing Mach number, which would be expected based on the tunnel mass balance and the LN_2 injection limitations placed on this mode of operation. For example, at Mach numbers of 0.765 and 0.860 the maximum removal rates are 1.85 and 2.00 percent, respectively. The shaded region shown in figure 8(a) represents the expected removal capability and requirement of the active system. The decrease in the upper bound of the expected removal capability with increasing Mach number (from a maximum value of 4.00 percent at a Mach number of 0.30 to a value of about 1.60 percent at a Mach number of 0.86) is primarily due to the mass flow limitations of the digital valves.

Active System

The data shown in figure 8(b) are the limited performance results of the active removal system obtained during the detailed compressor performance validation. The shaded region represents the range of performance of the passive system as shown in figure 8(a). The compressor performance validation was done over a wide range of stagnation pressures and temperatures (from a maximum mass removal condition to a condition of compressor surge) at test section Mach numbers of 0.40 and 0.73. At these two Mach numbers, numerous data points were taken to evaluate the compressor performance, as indicated by the crosshatched regions between the circle and the square. The upper dashed line between the two circles represents an approximate fairing of the upper limit of the performance of the active system, with the digital valves open 100 percent. In a similar manner, the lower dashed line is faired between the two squares, which are the points of minimum removal without recirculation. This line is also referred to as the compressor surge line. When the compressor is operated below the surge line with the active removal system, recirculation is required to keep it out of surge. The compressor validation was done with no recirculation in order to accurately measure the mass flow through the compressor with the two digital valves. At a Mach number of 0.40, the maximum removal rate is about 5.0 percent. As the Mach number increases the maximum removal rate shows the expected decrease. At the higher Mach number of 0.73, the maximum removal rate for the active system is about 2.5 percent, which is about 35 percent higher than the passive removal value of 1.85 percent. The compressor was not operated below the surge line during the limited active system performance validation tests reported in this paper. When recirculation (i.e., operation below the surge line; see fig. 4) is utilized, the envelope of the active removal capabilities includes the entire region from the maximum removal condition (i.e., digital valves fully open) down to, and in some cases including, the region of passive operation. Clearly, the results from figure 8(b) indicate the addition of the cryogenic compressor greatly expands the operational capability of the sidewall-boundary-layer removal system at the lower test section Mach numbers.

Compressor Validation

Compressor performance for total-head pressure ratio and power versus inlet flow in actual cubic feet per minute are shown in figures 9 and 10. The inlet flow in both figures is reduced to the design condition using ideal gas nitrogen calculations (compressibility factor of 1.0), an inlet pressure of 46.6 psia, an inlet temperature of 410°R, and a motor speed of 2180 rpm. The actual compressor inlet pressure and temperature varied from 7 to 37 psia and from 160°R to 410°R, respectively, during the tests. The steady-state inlet temperatures for the compressor were very close to the tunnel total temperature. However, as would be expected, because of the pressure drop between the test section perforated plates and the compressor inlet, the inlet pressures (see figs. 9 and 10) were considerably less than the tunnel total pressures of 17.6 to 85.0 psia. The performance data were taken with the recirculation loop closed, and the removal rates ranged from the maximum flow rate the digital valves could pass to the rate at which compressor surge was first detected. In addition, there was no LN_2 injected between the digital valve and the compressor inlet. Thus, all the mass that passed through the compressor came from the sidewall-boundary-layer removal and was directly reinjected into the tunnel. During the tests, the tunnel flow conditions could be easily maintained, indicating successful integration of the compressor system with the tunnel operation. The measured pressure ratio data in figure 9 are very close to the expected values from design calculations. In addition, the results in figure 9 confirm the design logic used in the pressure ratio/surge controls which required the actual pressure ratio to be slightly above the set point value of 2.15. This pressure ratio control process always puts the compressor in an operating condition of higher flow and away from surge. The required compressor power (see fig. 10), calculated from the measured mass flow, pressure, and temperature during the compressor validation, shows that compressor power requirements will not exceed the available 1000 hp of the drive motor.

Conclusions

Tests were conducted in the 0.3-m TCT with the recently installed active sidewall-boundary-layer removal system to validate the operation of a new cryogenic compressor and the associated system controls. During the tests the mass removed from the sidewall boundary layer of the test section was reinjected into the high speed diffuser section. The tunnel was in a standard mode of operation for airfoil testing, with an airfoil in the test section. The tests were conducted at a subsonic and a near transonic Mach number over a wide range of stagnation pressures and temperatures. The integration of the active sidewall-boundary-layer removal system was evaluated and some limited performance data were obtained for the active system. The tests indicate the following conclusions:

1. The active sidewall-boundary-layer removal system was successfully integrated with the normal operation of the tunnel. The new system used a cryogenic centrifugal compressor to reinject the mass removed from the test section back into the high-speed diffuser.
2. The active system with the compressor operated successfully over a range of tunnel total pressures (17.6 to 85.0 psia) and tunnel total temperatures (near ambient to the saturation limit).
3. The digital valves previously used in the passive system were integrated into the active system and provided an accurate control of the rate of sidewall-boundary-layer mass removal.
4. The limited performance validation indicated the boundary-layer removal capability was greatly expanded by the active system at the lower test section Mach numbers. At a test section Mach number of 0.40, about 5.0 percent of the test section mass flow was removed with the active system compared with about 0.25 percent removed with the passive system, and at a near transonic Mach number of 0.73 the active system removed 2.5 percent of the test section mass flow compared with 1.85 percent removed with the passive system.
5. The compressor pressure ratio performance was close to the design values for all removal rates over the range of tunnel operating conditions.
6. The required power of the compressor never exceeded the available power of the drive motor for all flow rates and over the range of tunnel operation conditions tested.

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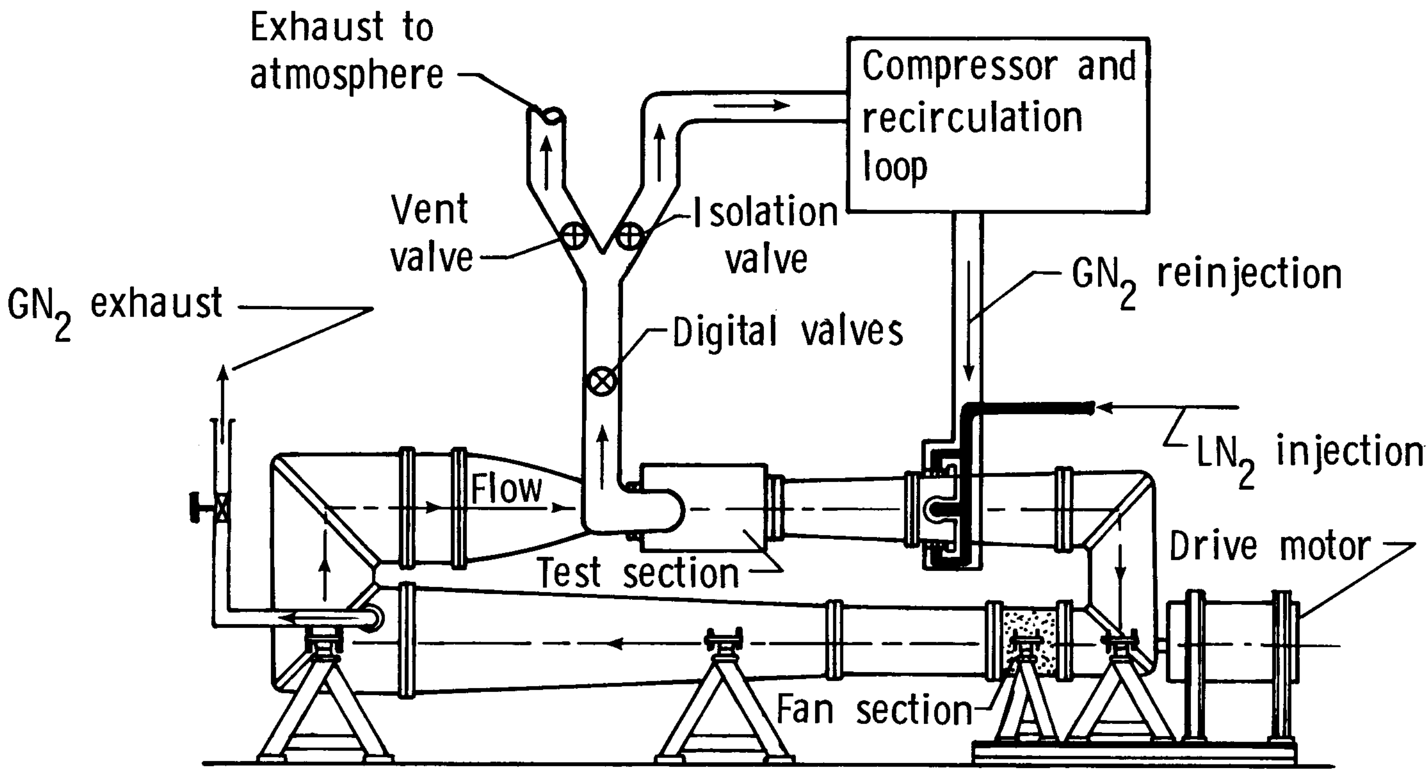

Figure 1. Schematic of 0.3-m TCT with boundary-layer removal system.

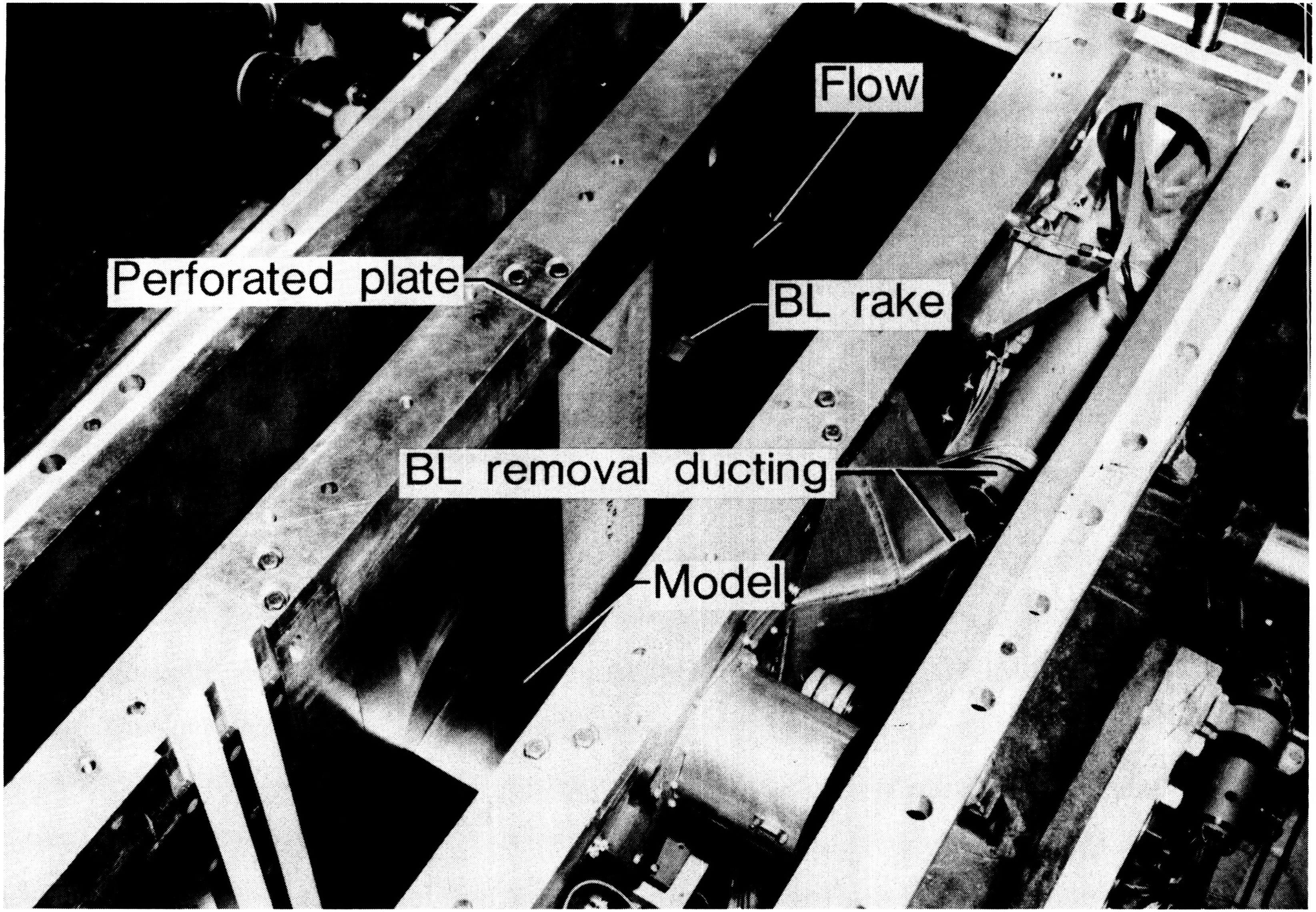

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Figure 2. Two-dimensional test section of 0.3-m TCT with perforated plates used for sidewall-boundary-layer removal.

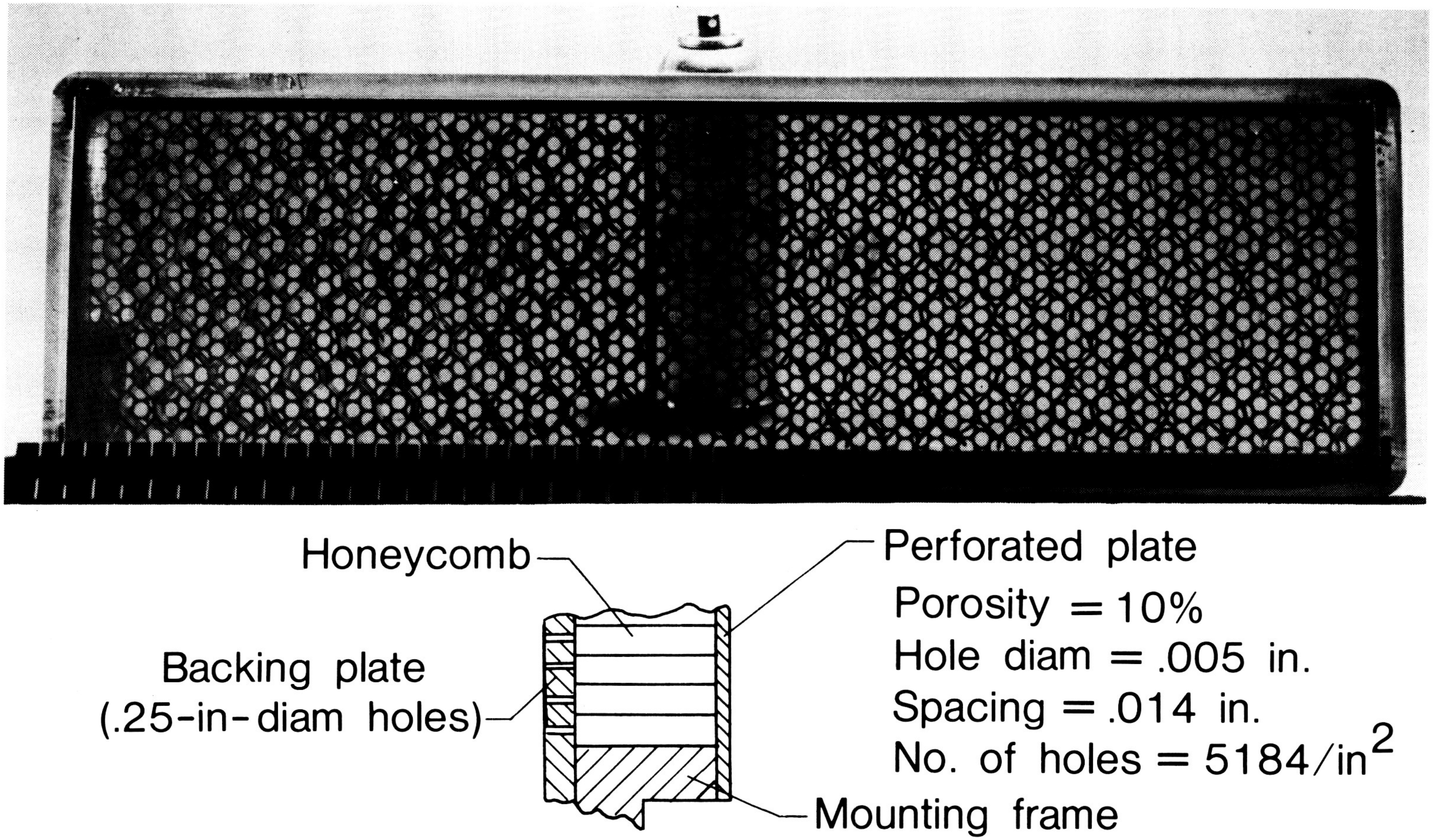

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Figure 3. Assembly of perforated plates used for sidewall-boundary-layer removal.

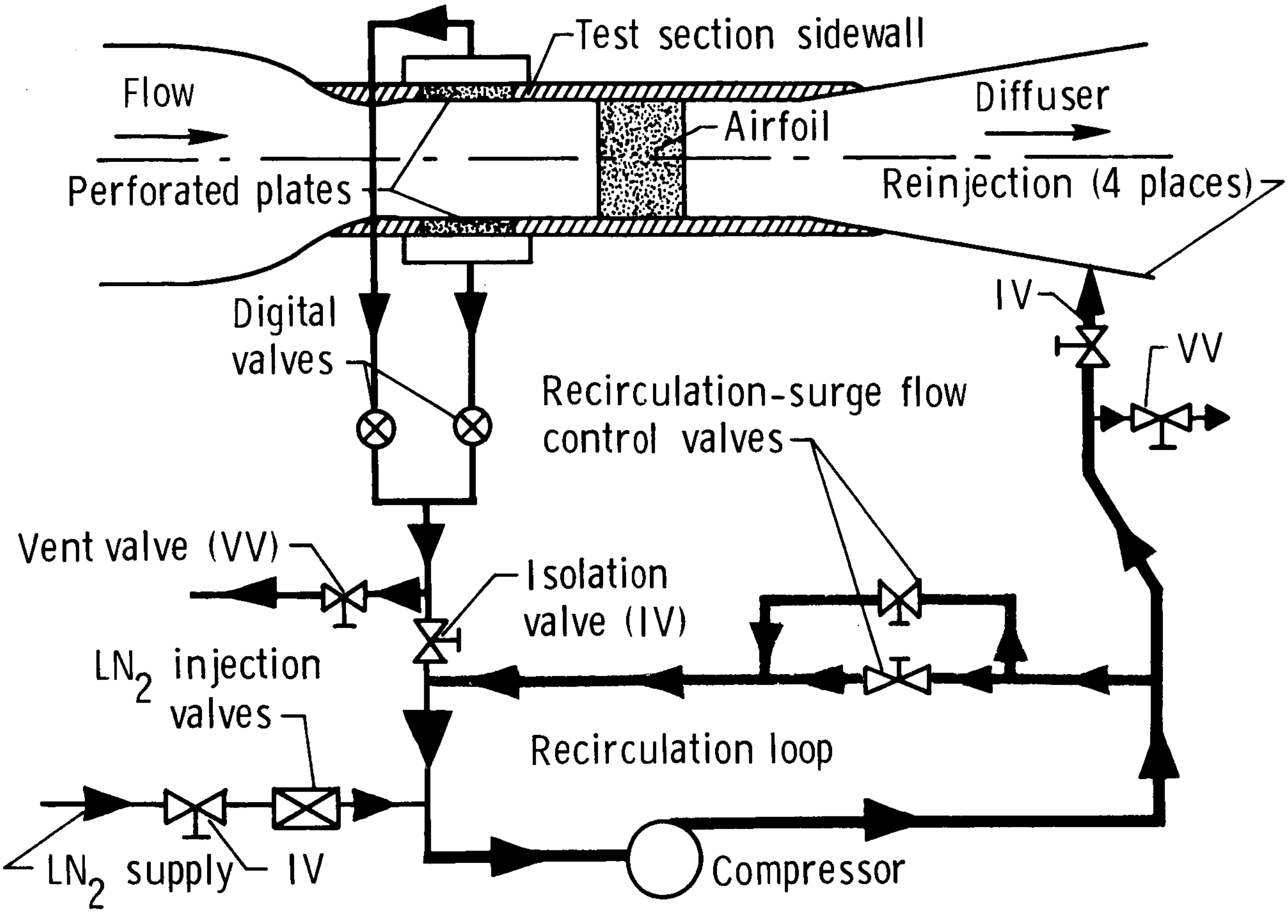

Figure 4. Schematic of boundary-layer removal system.

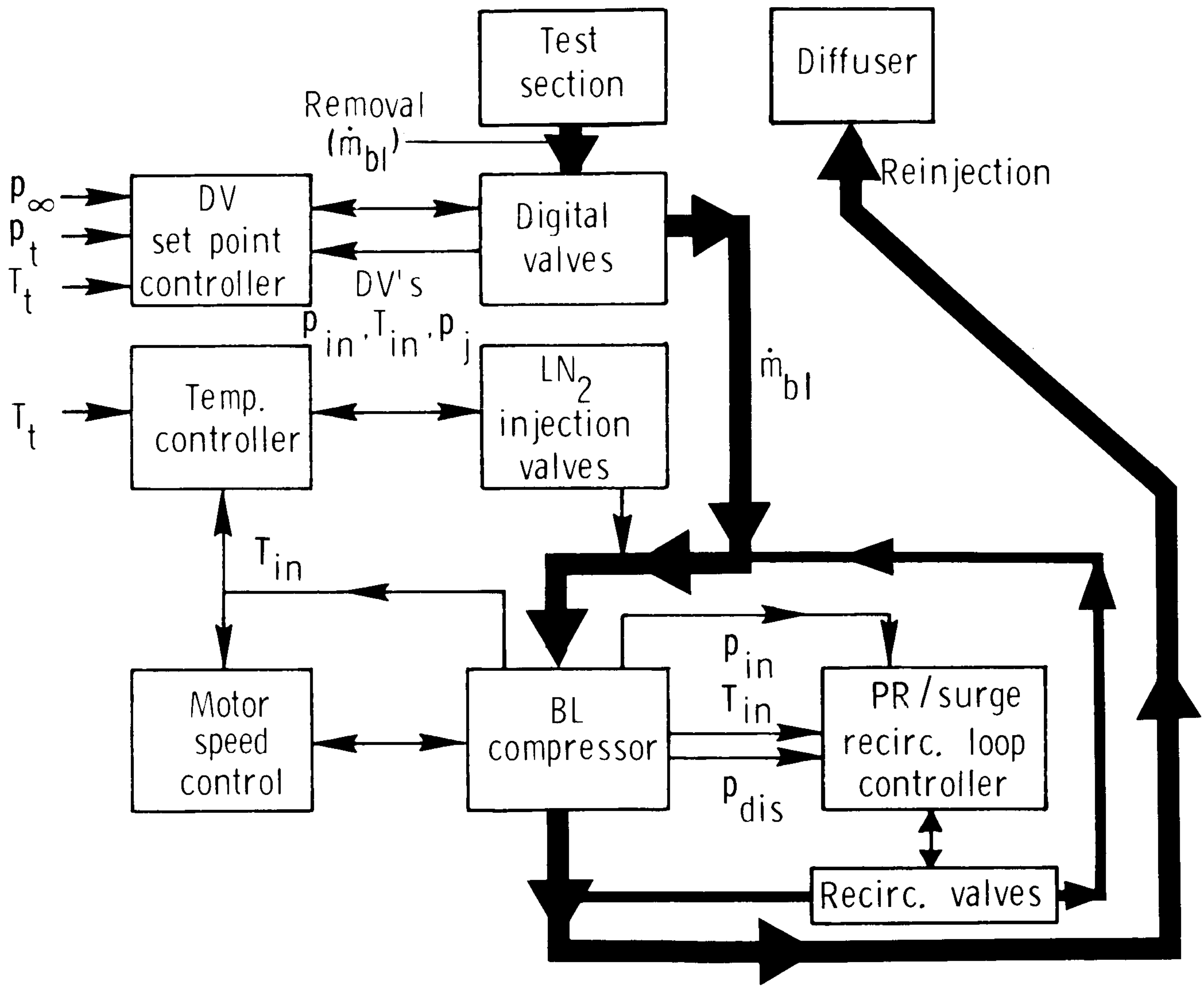

Figure 5. Diagram of the control features of the boundary-layer removal system.

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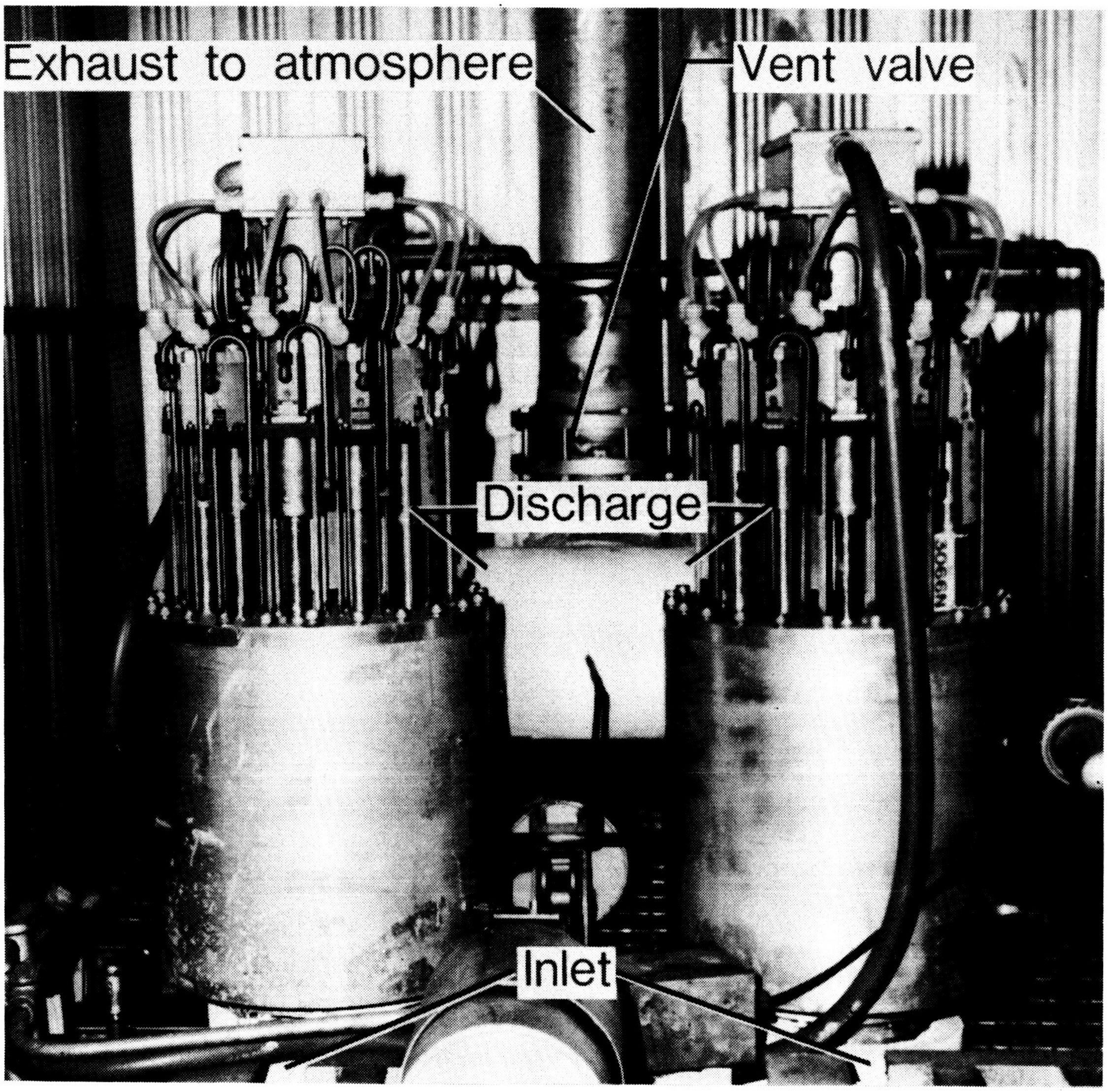

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Figure 6. Digital valves used to regulate boundary-layer removal.

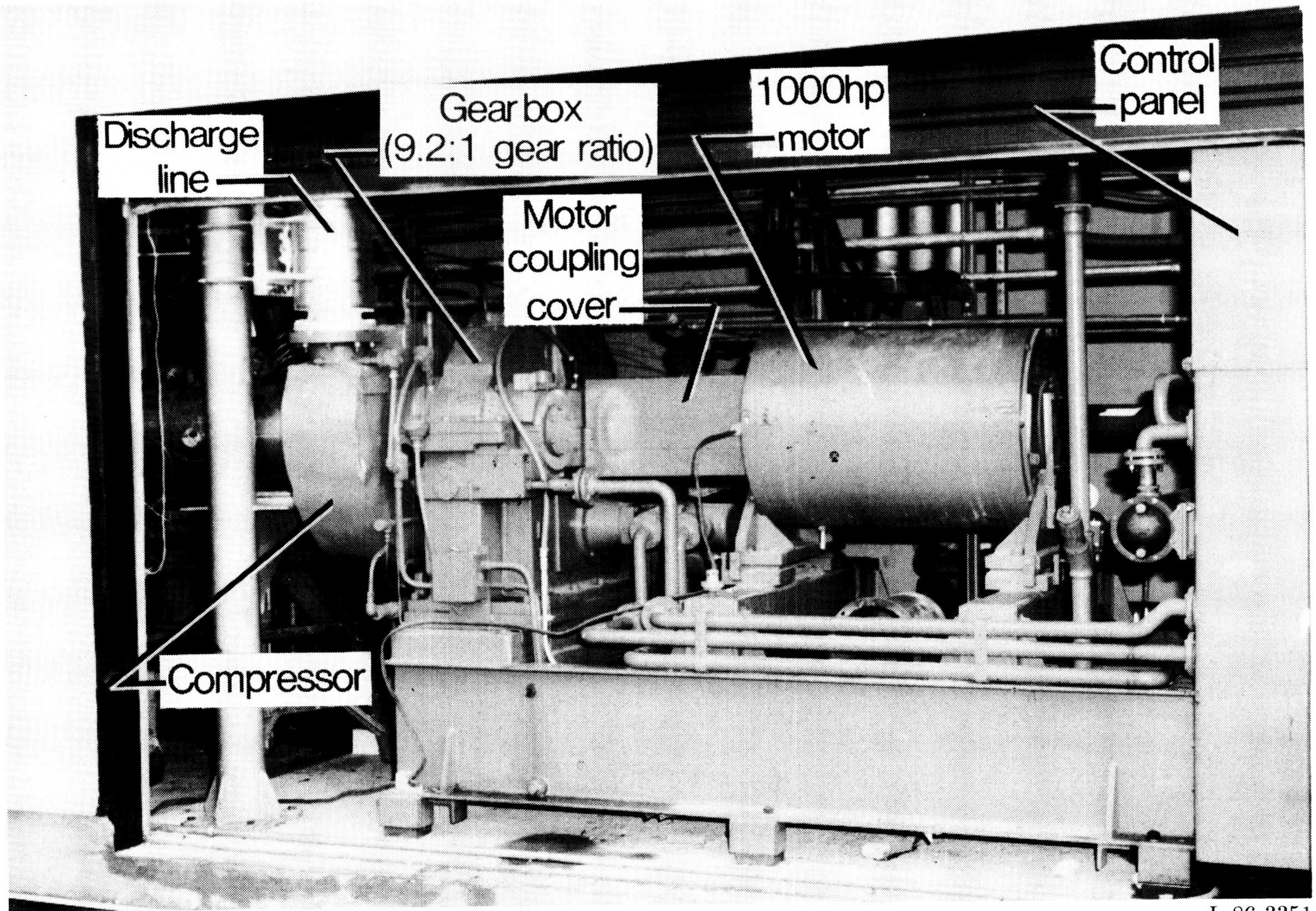

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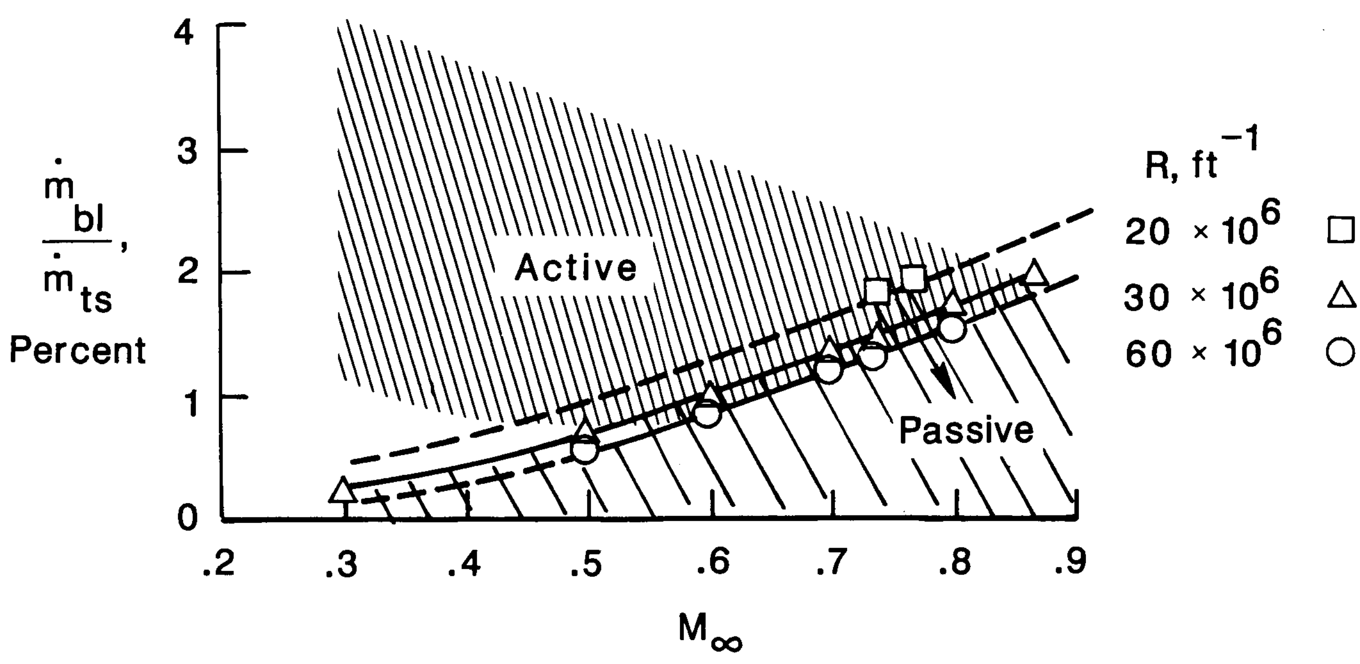
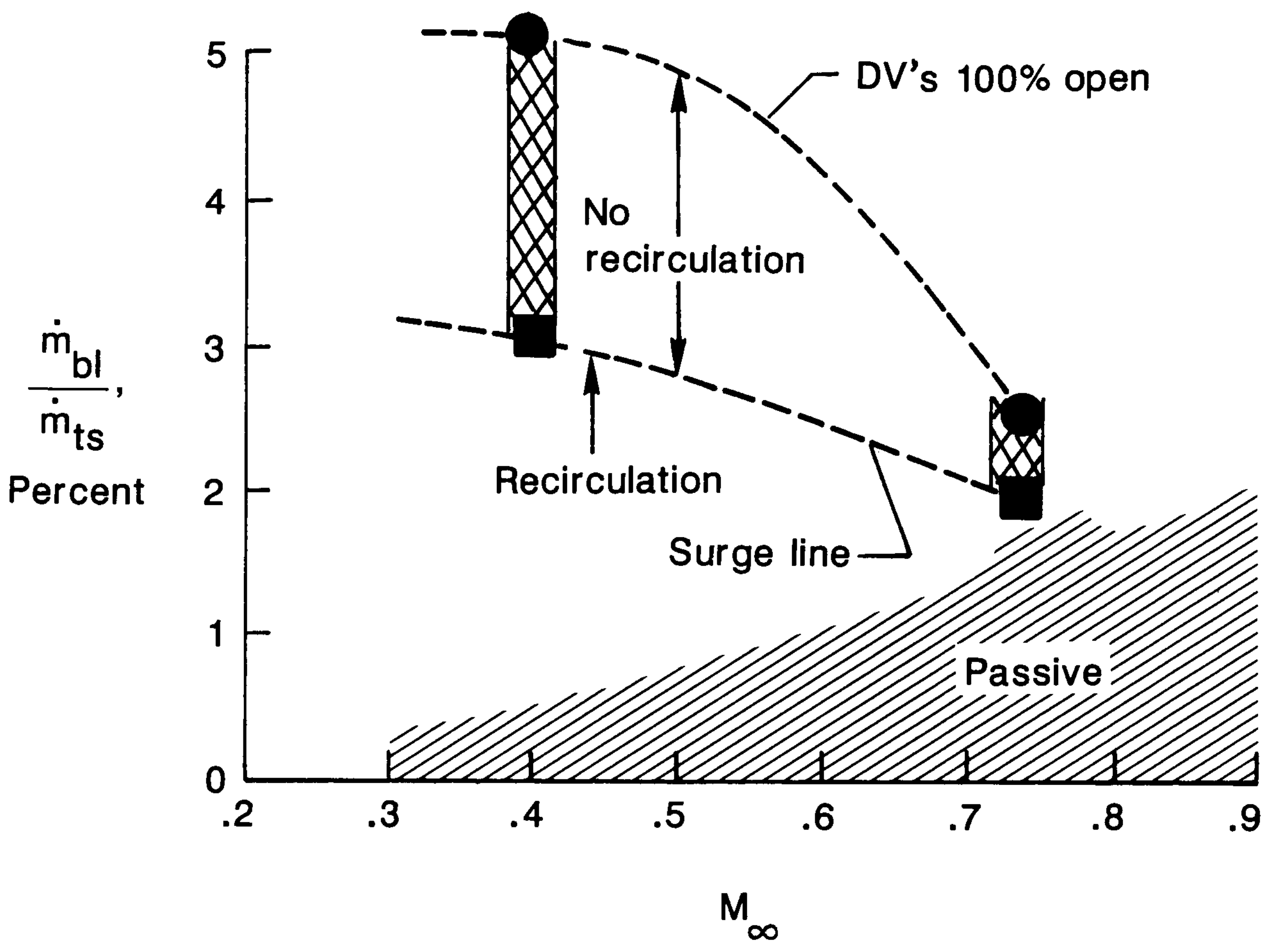
Figure 7. Compressor drive system used with active sidewall-boundary-layer removal system.



(a) Passive system data with active system requirements.

Figure 8. Performance of sidewall-boundary-layer removal system (8- by 24-in. test section).



(b) Active system data (with compressor reinjection) and passive capability.

Figure 8. Concluded.

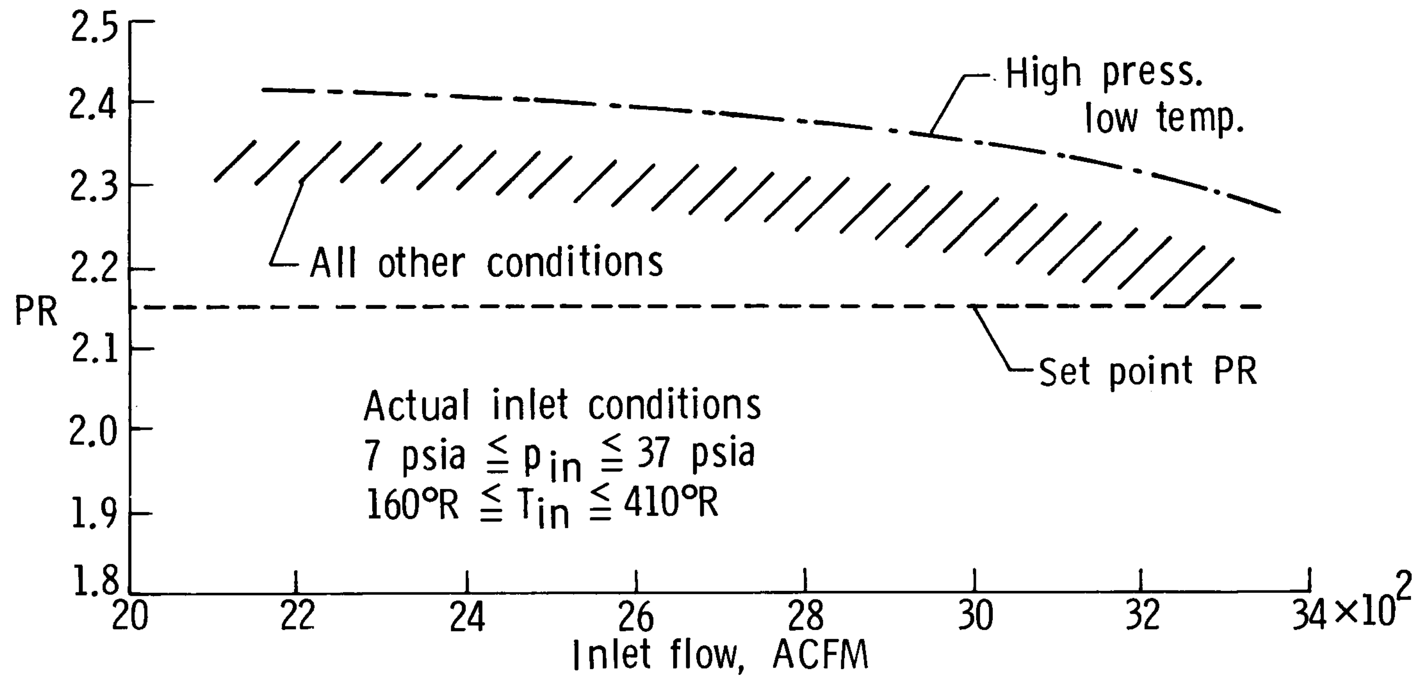


Figure 9. Total-head pressure ratio of compressor from performance test. All data reduced to p_{in} = 46.6 psia and T_{in} = 410°R at 2180 rpm.

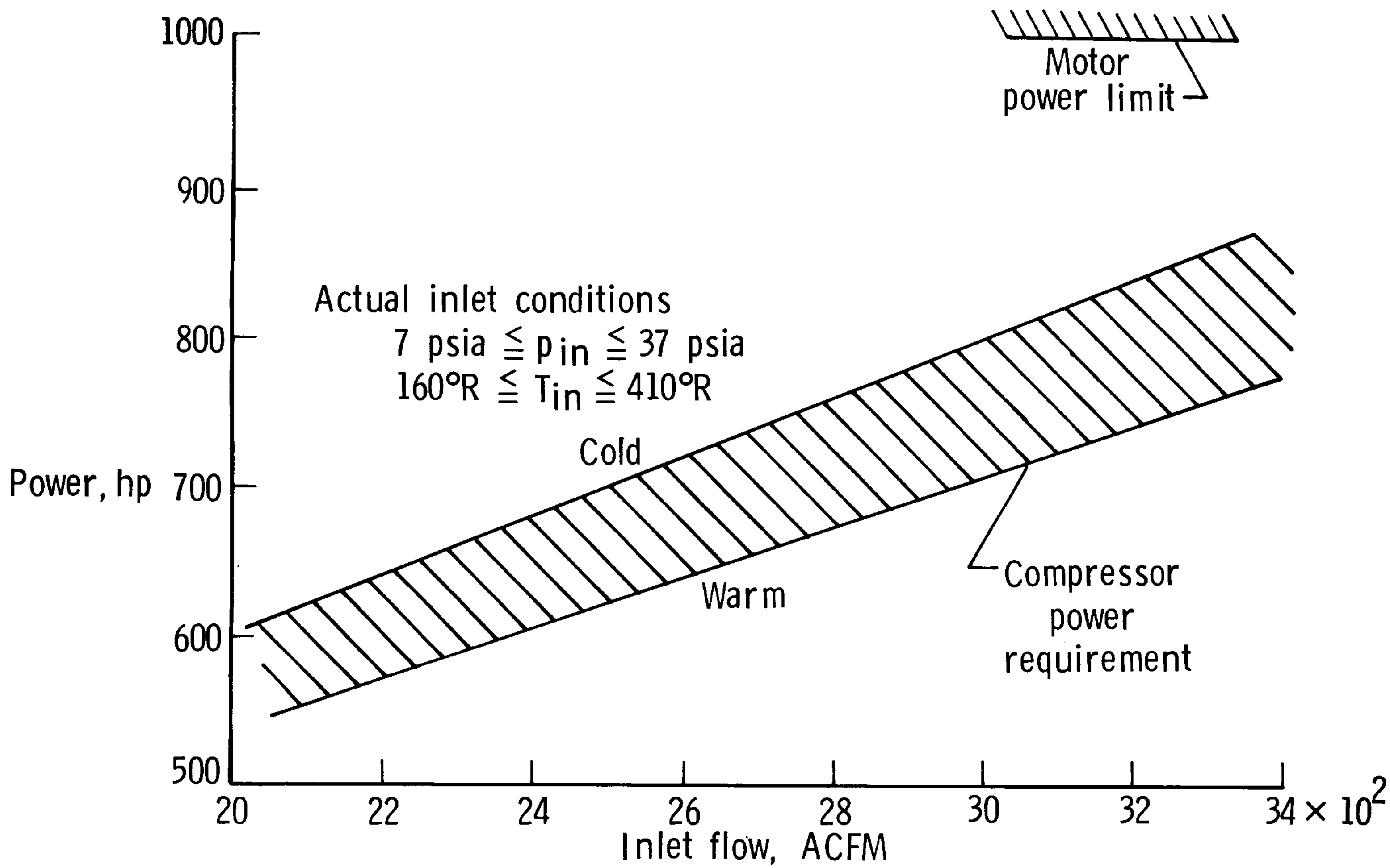


Figure 10. Required power of compressor from performance test. All data reduced to p_{in} = 46.6 psia and T_{in} = 410°R at 2180 rpm.

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16. Abstract

Results are presented for an operational checkout and shakedown of the active sidewall-boundary-layer removal system newly installed in the Langley 0.3-meter Transonic Cryogenic Tunnel (0.3-m TCT). Prior to the installation of this active removal system, the sidewall-boundary layer was removed passively by exhausting directly to the atmosphere (i.e., no reinjection). With the active removal system using the reinjection compressor, the removal capability is greatly expanded to cover the entire operating envelope of the 0.3-m TCT. Details of the active removal system are presented including the compressor reinjection circuit, the compressor pressure ratio/surge control, and the compressor recirculation loop. The control logic and features of the compressor surge control are explained. Initial tests covering critical operating conditions show mass flow removal rates of about 5 percent at lower Mach numbers can be obtained with the active system. Measured performance characteristics of the compressor are presented. As part of the validation of the active system, limited airfoil tests were made using the new system.

17. Key Words (Suggested by Authors(s))		18. Distribution Statement	
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