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JUNE 1977

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EFFECT OF LN_2 INJECTION STATION LOCATION ON THE DRIVE FAN POWER AND LN_2 REQUIREMENTS OF A CRYOGENIC WIND TUNNEL

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ABSTRACT

This theoretical analysis consists of comparing the fan power and LN_2 flow rates resulting from the injection of LN_2 either upstream or downstream of the fan of a closed circuit transonic cryogenic tunnel. The analysis is restricted to steady-state tunnel operation. The results show that the fan power and LN_2 flow rates are lower if the LN_2 is injected upstream of the fan.

SUMMARY

The theoretical analysis of this report compares the fan power and coolant (LN_2) flow rates resulting from injection of the LN_2 either upstream or downstream of the drive fan of a closed circuit transonic cryogenic tunnel. The analysis is restricted to steady-state tunnel operation and to the condition that the tunnel walls are adiabatic. The stagnation pressure and temperature range of the tunnel is from 1.0 to 8.8 atm and from 300 K to liquefaction temperature, respectively. The calculations are made using the real-gas properties of nitrogen. The results show that the fan power and LN_2 flow rates are lower if the LN_2 is injected upstream of the fan. The lower fan inlet temperature resulting from injecting upstream of the fan has a greater influence on the power than does the additional mass flow going through the fan.

INTRODUCTION

A new transonic wind tunnel that will satisfy the nation's high Reynolds number test needs is currently being designed at the Langley Research Center (ref. 1). This tunnel is based on the cryogenic concept that was developed and demonstrated at Langley (refs. 2, 3). One of the main advantages of reducing the temperature of the test gas as a means of obtaining the desired high Reynolds number capability is that a large reduction in tunnel size is afforded while maintaining acceptable stagnated pressures thereby resulting in large savings in capital cost.

For this concept, reduction of the test gas temperature and the removal of the heat generated by the drive fan and the heat conducted through the walls of the tunnel is accomplished by pumping liquid nitrogen into the circuit and letting it vaporize. The location in the tunnel circuit for this LN_2 injection is being studied in the design of the above mentioned tunnel. Some of the considerations are: sufficient distance upstream from the test section in order to insure thorough mixing and uniform temperatures at the test section, excessive thermal stresses and possible material errosion due to LN_2 droplets impinging on internal structures, and the effect of the location of the injection relative to the drive fan on tunnel drive power and LN_2 consumption. The purpose of this paper is to present an analytical comparison of the drive power and LN_2 requirements associated with LN_2 injection upstream and downstream of the drive fan.

SYMBOLS

C_p	specific heat at constant pressure, J/(kg·K)
$\dot{E}$	flow of energy per unit time, J/sec
h	specific enthalpy, J/kg
$\dot{m}$	mass-flow rate, kg/sec
p	pressure, atm
r	fan total pressure ratio, $p_{t,4}/p_{t,3}$
T	temperature, K
$\dot{W}$	work per unit time or power, J/sec
γ	ratio of specific heats
ρ	density, kg/m^3

Subscripts

DN	downstream of fan
e	exhaust gas
F	fan
i	LN_2 injected

s constant entropy

t stagnation condition

UP upstream of fan

0,1,2,3,4,5 tunnel station numbers

ANALYTICAL MODEL AND PROCEDURE

The operational mode of the cryogenic tunnel to be considered in this analysis is the steady-state mode (i.e., constant stagnation temperature, stagnation pressure, and test section Mach number). The test conditions to be considered encompass the envelope of the tunnel that is under design. The stagnation pressure range is from 1.0 to 8.8 atm and the stagnation temperature range is from ambient temperatures (300 K) down to liquefaction temperatures (80-120 K, depending on pressure). The fan pressure ratios necessary to achieve a given test section Mach number in the closed-circuit fan-driven tunnel are assumed to be as follows:

M_1	r
0.2	1.025
0.6	1.050
0.8	1.075
1.0	1.100
1.2	1.200

It is further assumed that this Mach number-pressure ratio correspondence is invariant with stagnation temperature and pressure. In these calculations, the real gas properties of nitrogen as given by Jacobsen's equation of state (ref. 4) will be utilized.

A sketch of the analytical model tunnel is shown in figure 1. There is a supply reservoir where LN_2 is stored at 1.0 atm and the corresponding vapor temperature. From this reservoir LN_2 is pumped into the tunnel at either the upstream injection station (2) or the downstream injection station (4). This pumping is assumed to be isentropic and it is further assumed that the liquid must be pumped to the stagnation pressure at the injection location. In actuality, the liquid would probably have to be pumped to a pressure higher than the stagnation pressure, but that additional pumping has a negligible effect on the energy of the liquid nitrogen going into the tunnel. When the LN_2 is injected at the upstream station, it is assumed that the cooling process is complete prior to the flow being compressed at the fan. In order to achieve steady-state conditions, gaseous nitrogen is exhausted from the settling chamber of the tunnel at the same mass flow rate that LN_2 is added.

The following general assumptions apply to this analytical tunnel irregardless of where the LN_2 is being injected. First, the tunnel is assumed to be perfectly insulated (i.e., adiabatic). In actuality, there would be some heat conducted through the walls, but even at low Mach numbers where the fan power is low, this heat energy is only about 10 percent of the fan energy. Second, all of the tunnel stagnation pressure losses due to friction and separation occur between the test section and the upstream injection station. Third, the fan compression is isentropic.

Application of the first law of thermodynamics is now made to this analytic tunnel. The energies that cross the system boundaries (tunnel walls) are the energy of the LN_2 being injected, the work being done on the flow by the fan, and the energy of the gaseous nitrogen that is exhausted. The energy equation for the system in rate form is

$$\dot{W} + \dot{E}_i = \dot{E}_e \tag{1}$$

With the assumptions that have been made, the stagnation conditions at the various stations in the tunnel are sufficiently known so that the terms of this equation can be evaluated. These stagnation conditions are given in the following tabulation. Note that the stagnation pressures around the circuit are independent of where the injection occurs.

Station	p_t	T_t	
		Upstream injection	Downstream injection
1	$p_{t,1}$	$T_{t,1}$	$T_{t,1}$
2	$p_{t,2} = p_{t,1}/r$	$T_{t,2} = T_{t,1}$	$T_{t,2} = T_{t,1}$
3	$p_{t,3} = p_{t,2}$		$T_{t,3} = T_{t,1}$
4	$p_{t,4} = p_{t,1}$	$T_{t,4} = T_{t,1}$	
5	$p_{t,5} = p_{t,1}$	$T_{t,5} = T_{t,1}$	$T_{t,5} = T_{t,1}$

First, consider the solution of the energy equation for the upstream injection case. The rate that energy is being injected is given as

$$\dot{E}_i = \dot{m}_i h_i$$

The enthalpy of the injected liquid is

$$h_i = h_o + \int_{p_o}^{p_{t,2}} \left(\frac{1}{\rho}\right) dp$$

The second term is the isentropic pumping of the liquid to the stagnation pressure at the injection station. The density of the liquid is essentially constant for the pressure range of this study and is evaluated at storage conditions. The rate that energy is being exhausted from the tunnel is

$$\dot{E}_e = \dot{m}_e h_e = \dot{m}_i h_e$$

The exhaust enthalpy, h_e, is evaluated at the stagnation conditions at the exhaust station. The remaining energy term is the isentropic compression work at the fan and is given as

$$\dot{W} = \dot{m}_F \left(\Delta h_{t,F}\right)_s = \left(\dot{m}_1 + \dot{m}_i\right)\left(\Delta h_{t,F}\right)_s \tag{2}$$

With the stagnation conditions downstream of the fan and the stagnation pressure upstream of the fan known, the remaining stagnation conditions upstream of the fan can be determined by the real-gas procedures outlined in reference 5. The test section mass flow rate, $\dot{m}_1$, is also calculated using the procedure of reference 5.

When these three energy terms are inserted into the energy equation, an expression for the LN_2 flow rate results.

$$\dot{m}_i = \frac{\dot{m}_1\left(\Delta h_{t,F}\right)}{\left(h_i - h_e - \Delta h_{t,F}\right)} \tag{3}$$

With the LN_2 flow rate known, the fan work rate or power is calculated from equation 2.

Now consider the case of injection downstream of the fan. The energy of the LN_2 being injected is calculated using the same formula as before with the only difference being the stagnation pressure to which the LN_2 has to be pumped.

$$\dot{E}_i = m_i h_i = \dot{m}_i\left(h_o + \int_{p_o}^{p_{t,4}} \left(\frac{1}{\rho}\right) dp\right)$$

The energy of the exhausting gaseous nitrogen is calculated in the same manner as before and the power of the fan is

$$\dot{W} = \dot{m}_1\left(\Delta h_{t,F}\right)_s \tag{4}$$

For this case, the stagnation conditions upstream of the fan are known along with the stagnation pressure downstream of the fan. By working along a line of constant entropy the remaining stagnation conditions downstream can be determined.

Since the injected LN_2 does not go through the fan, the fan power can be determined prior to the determination of the LN_2 flow rate. The LN_2 flow rate is again determined by substituting the energy terms into the energy equation.

$$\dot{m}_i = \frac{\dot{m}_1\left(\Delta h_{t,F}\right)_s}{h_e - h_i}$$

For the analysis, a given set of tunnel conditions $\left(p_{t,1},\ T_{t,1},\ M_1,\ r\right)$ are chosen, then the fan power and LN_2 flow rates are determined for both the upstream and downstream injection cases.

RESULTS

A comparison of the fan power and LN_2 flow rates for a fan pressure ratio and Mach number of 1.2 is presented in figure 2. The fan power for upstream injection is always less than that for downstream injection with this difference becoming greater as stagnation temperature is reduced. At the maximum pressure (8.8 atm) and minimum operating temperatures, this difference is approximately 5.0 percent. As the pressure is reduced to 1 atm, the difference drops to about 3.0 percent. For an explanation of why the fan powers for upstream injection are lower, it is instructive to look at an ideal gas form of equation 2.

$$\dot{W} = \left(\dot{m}_1 + \dot{m}_i\right)\left[C_p\ T_{t,3}\left(r^{\frac{\gamma - 1}{\gamma}} - 1\right)\right]$$

The term in brackets represents the energy per unit mass required for the compression. This term is reduced for reduced fan inlet temperatures, $T_{t,3}$ as is the case for upstream injection. Counter to this effect is the increased mass flowing through the fan. The first effect dominates however. For example at maximum pressure and minimum temperature, the energy per unit mass for upstream injection is about 7.5 percent lower than for downstream injection while the LN_2 flow rate is about 2.3 percent of the test section flow rate. This results in a power decrease of 5.2 percent.

For a given set of stagnation conditions, the ratio of LN_2 flow rates is almost identical to the power ratio. The reason for this is not obvious by looking at the LN_2 flow rate equations (3 and 5). Intuitively though this is the expected result, because the only energy that has to be counteracted by the cooling capacity of the LN_2 is the work being done by the drive fan. This of course assumes that the cooling capacity is not appreciably affected by changes in injection location. Since the LN_2 flow rate ratio is essentially equal to the power ratio in subsequent figures only the power ratio will be presented.

For the same fan pressure ratio — Mach number combination, figure 3 shows the power ratio as a function of stagnation pressure for constant values of stagnation temperature. The benefits of upstream injection decrease linearly with stagnation pressure except at the lowest stagnation temperature.

The effect of fan pressure ratio on the power ratio is shown in figure 4. These particular fan pressure ratios are typical of the various test section Mach numbers as outlined previously. It turns out that these power curves are only a function of the fan pressure ratio. Any other Mach number assigned to the same fan pressure ratio results in the same power ratio curve. These curves show that as the tunnel pressure losses are reduced (low fan pressure ratio), the benefits from upstream injection are reduced accordingly.

One of the assumptions that was made for the analytical model tunnel was that all of the tunnel total pressure losses occurred prior to the upstream injection station. A brief study was made with the total pressure losses distributed around the tunnel similar to what is expected for the tunnel presently being designed (ref. 6). The distributed losses had a negligible effect on the fan power and LN_2 flow rate curves.

CONCLUDING REMARKS

This theoretical analysis has consisted of comparing the fan power and LN_2 flow rates resulting from the injection of LN_2 either upstream or downstream of the fan of a closed circuit transonic cryogenic tunnel. The analysis has been restricted to steady-state tunnel operation. The results show that the fan power and LN_2 flow rates are lower if the LN_2 is injected upstream of the fan. The reason for this is that the reduction in fan inlet temperature due to injecting upstream of the fan has a greater influence on the power than does the increased mass flow going through the fan.

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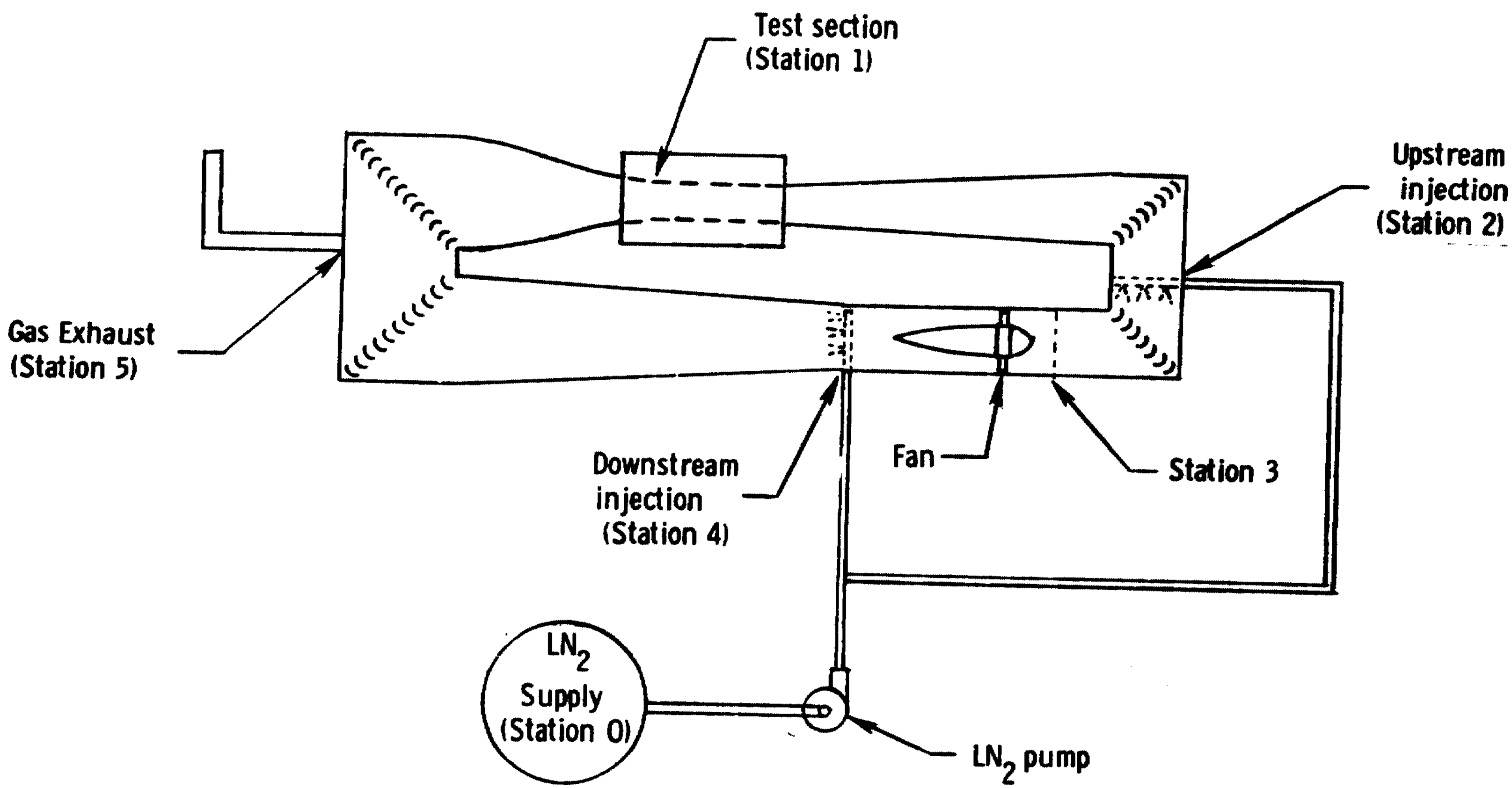


Figure 1. Sketch of analytical tunnel.

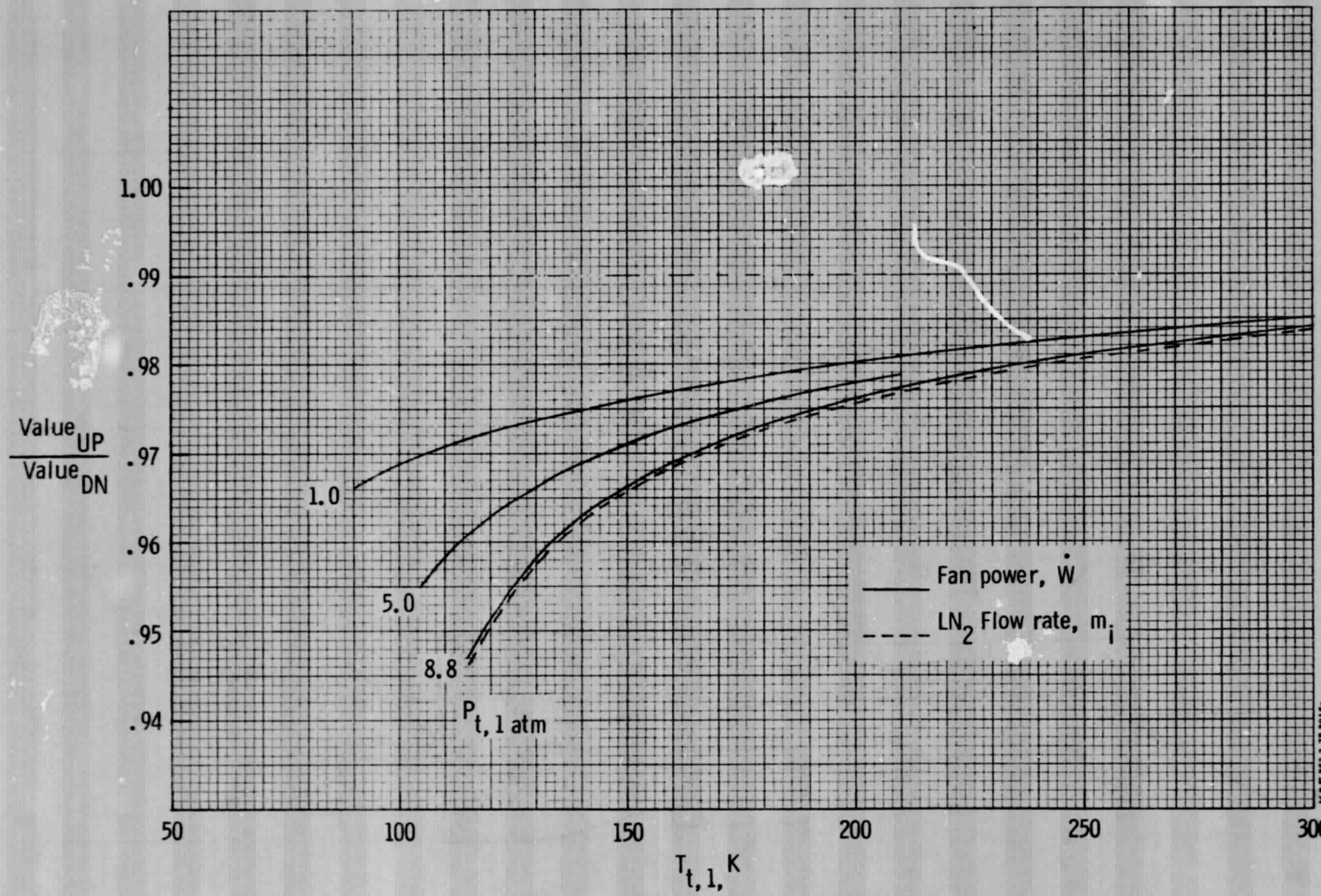


Figure 2. Comparison of fan power and LN_2 flow rates for LN_2 injection upstream and downstream of drive fan ($r = 1.2$, $M_1 = 1.2$)

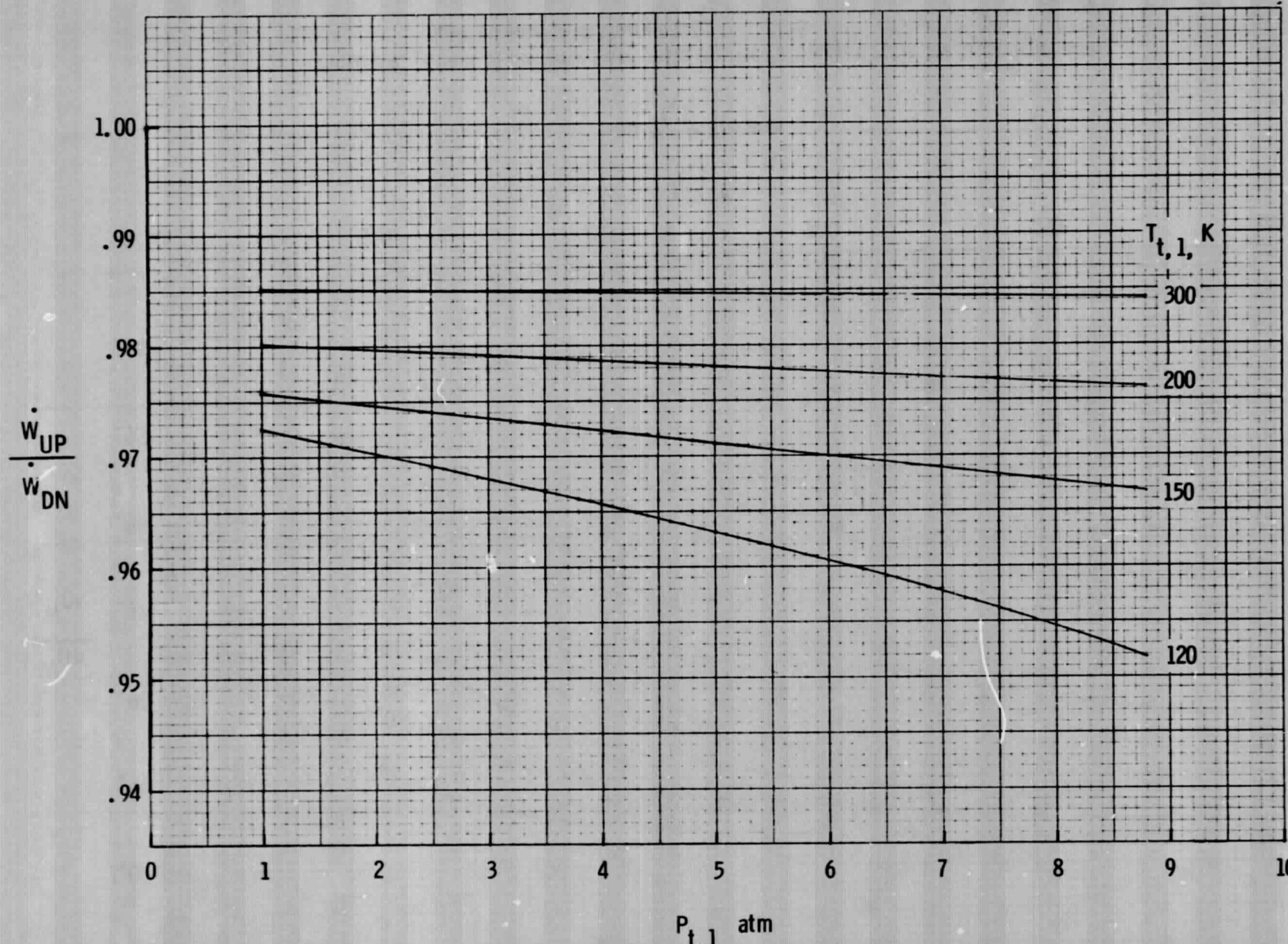
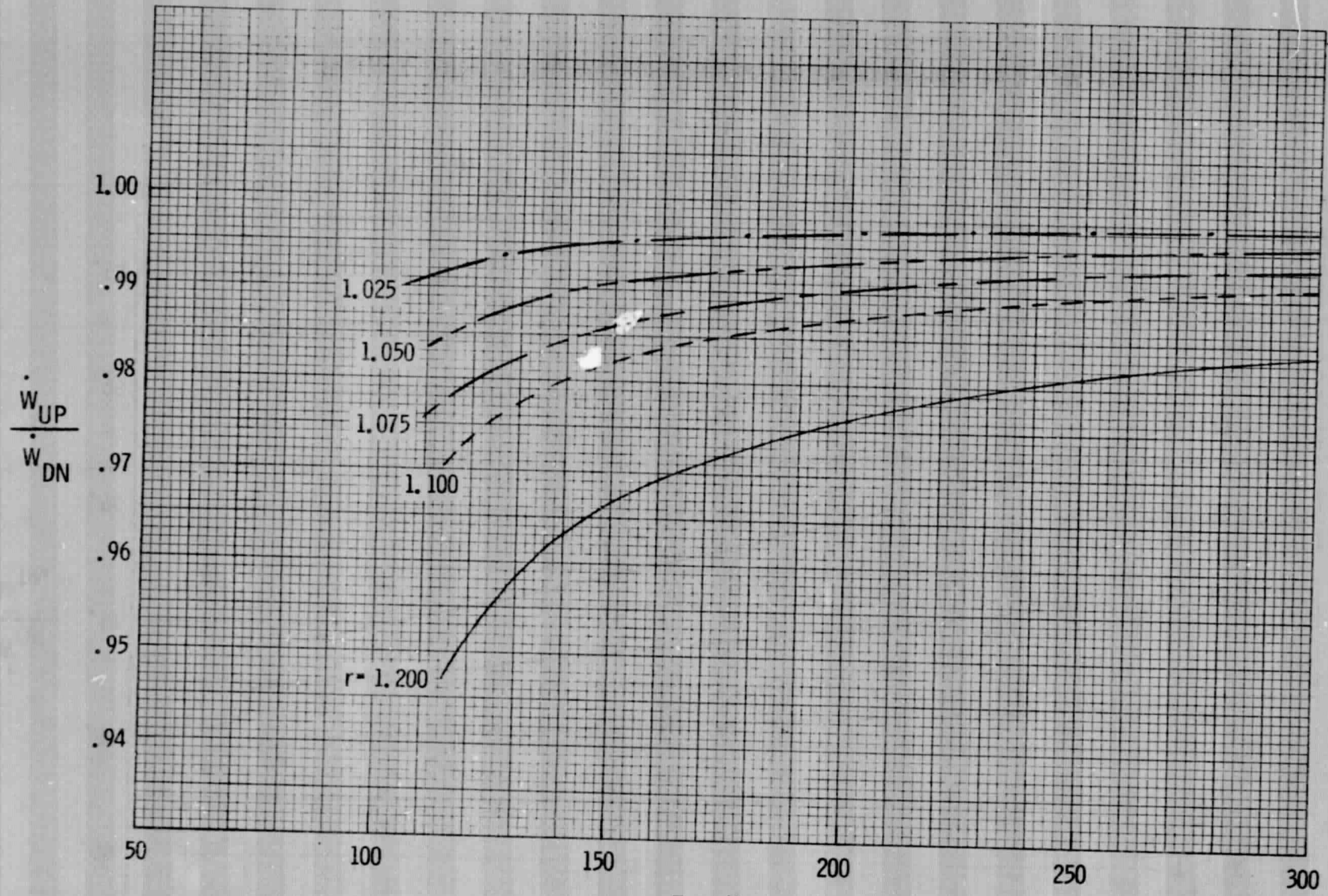
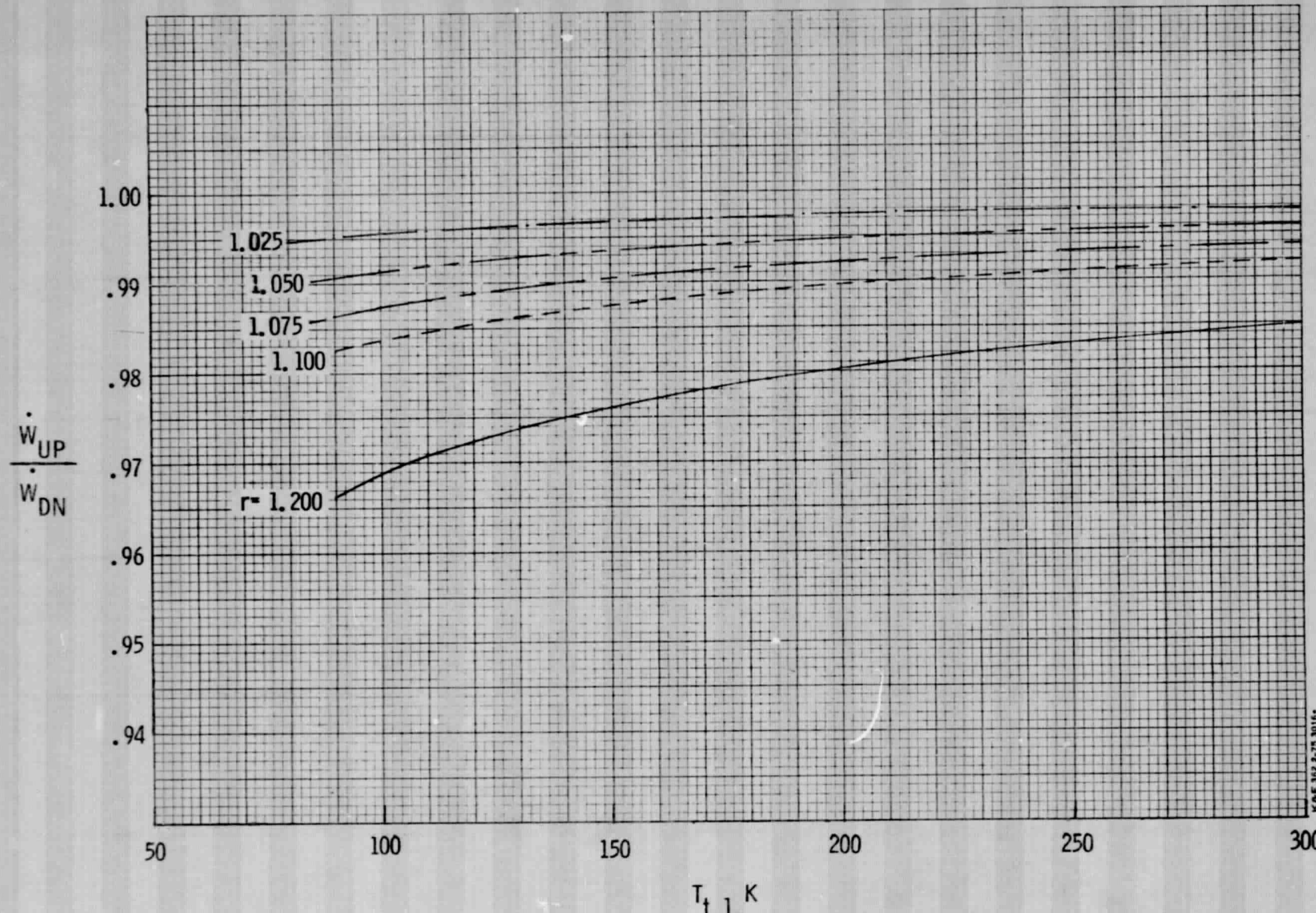


Figure 3. Effect of stagnation pressure on the fan power ratio ($r = 1.2$, $M_1 = 1.2$)



(a) $P_{t,1}$ = 8.8 atm

Figure 4. Effect of fan pressure ratio on the fan power ratio for upstream and downstream injection of LN_2.



(b) 1.0 atm

Figure 4. Concluded.

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16. Abstract

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