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# PERFORMANCE & ECONOMICS OF PRESSURISED & ATMOSPHERIC LOW SPEED WIND TUNNELS

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SUMMARY The performance of a series of pressurised low speed wind tunnels designed to operate at various maximum pressures between 2 and 5 atmospheres is analysed and compared with the performance of a geometrically similar atmospheric pressure tunnel on the basis of capital cost and power input. The choice of design of a new tunnel is usually influenced by cost and power considerations and it is important to obtain the most capable and economical tunnel within given values of these variables.

## NOTATION

$A$ = cross sectional area of working section
$C$ = capital cost of wind tunnel
$C_{dc}$ = capital cost of drive and cooling systems
$f$ = $C_{dc}/C$
$f_c$ = $m_p/m_a$ = cost factor
$g_c$ = $(n_p/n_a)^{1/m_a}$ = cost factor
$h$ = height of working section
$K$ = $[\eta_p(N_p/N_a)(1-k_{1p}-k_{2p})/(\eta_a(1-k_{2a}))]^{1/3}$
$k_1$ = $Np/N$
$k_2$ = $Nc/N$
$l_m$ = model length scale
$M_N$ = Mach number
$m$ = cost factor
$N$ = total power input
$Nc$ = drive power for cooling
$Np$ = drive power for pressurisation
$Nt$ = drive power for tunnel circuit
$n$ = cost factor
$P$ = pressure
$R_N$ = $\rho V l_m/\mu$ = Reynolds number
$r$ = Reynolds number length scale factor
$T$ = temperature (° abs)
$V$ = freestream velocity in working section
$w$ = width of working section
$\eta$ = tunnel efficiency (or energy ratio)
$\mu$ = viscosity of air
$\rho$ = density of air

Subscripts

$a$ = atmospheric tunnel
$D$ = design condition
$p$ = pressurised tunnel

## 1 INTRODUCTION

Pressurising a low speed wind tunnel has the advantage of allowing scale effects associated with $R_N$ and compressibility effects involving $M_N$ to be investigated separately. This can be important, particularly when testing V/STOL and other high lift aircraft model configurations at low freestream Mach numbers, because high local flow velocities associated with the production of high lift can lead to local compressibility effects which degrade performance. A pressurised tunnel may also have the advantage of a higher test $R_N$ than an atmospheric tunnel, and this can be very important in testing high lift wings and V/STOL aircraft. However, pressurised tunnels are less convenient to operate, both tunnel and model design are more complicated, and capital, operating and model costs are higher for a working section of the same size.

Any major new low speed tunnel will be very expensive and there will almost certainly be a limit on the funds available for its construction. It is therefore important to ensure that the most versatile tunnel with the 'best' performance is obtained within this constraint. In addition, high power costs make it necessary to minimise power consumption.

In this paper the performance of a series of tunnels designed to operate at various maximum pressures is estimated and compared with the performance of a similar atmospheric tunnel on the basis of capital cost and power input.

## 2 RELATIVE PERFORMANCE AND COST OF PRESSURISED AND ATMOSPHERIC TUNNELS

In the following analysis pressurised tunnels with maximum design pressures of 2, 3, 4 and 5 atmospheres are considered. The upper limit was determined by model strength considerations, while below about 2 bar there will not be a major increase in shell cost.

### 2.1 Capital Cost

The capital cost of a wind tunnel with a design pressure above about 2 bar will be much greater than an atmospheric tunnel of the same size. The additional cost mainly arises because -

1. the shell has to be built from steel, or relatively thick reinforced concrete, compared with timber, concrete, or relatively thin steel for an atmospheric tunnel;
2. to make the tunnel more productive and convenient to operate, a pressure shell must be placed around the entire working area with doors opening to the tunnel circuit and to atmosphere to enable access for both models and personnel by depressurising only the working section part of the circuit;
3. compressors, air storage, air driers, piping and connectors are needed, and the shell must be pressure tested.

As an indication of relative costs Spence and Spee (1972) estimated that the capital cost of a major tunnel designed to be pressurised to around 3 atmospheres is about 3 to 4 times the cost of an atmospheric tunnel of the same size.

In the following analysis, costs are considered in broad terms which are sufficient to give relative performance when initially evaluating atmospheric and pressurised tunnels. Information available indicates that the capital cost of an atmospheric tunnel is proportional to the cross-sectional area of the working section (or the smaller section of a tandem design) plus the cost of the main drive and cooling systems, and this can be expressed as

$$C_a = n_a A_a^{m_a} + C_{dc,a} \tag{1}$$

For a similar pressurised tunnel with a maximum design pressure between approximately 2 and 5 atmospheres the capital cost can be expressed as

$$C_p = n_p A_p^{m_p} + C_{dc,p} \tag{2}$$

If $C_{dc,a} = f_a C_a$ and $C_{dc,p} = f_p C_p$ then the sectional area of the atmospheric tunnel is given by

$$A_a = g_c A_p^{f_c} [C_a/C_p]^{1/m_a} [(1-f_a)/(1-f_p)]^{1/m_a} \tag{3}$$

where $g_c = (n_p/n_a)^{1/m_a}$ and $f_c = m_p/m_a$.

Capital cost includes the cost of the shell and its components, the working section and pressure isolation chamber, the cooling system, compressors, air storage, fan, drive system, balances, stings, and control and electrical systems, but not site preparation or buildings.

## 2.2 Power Consumption

Taking the power input as the sum of the power to move air around the tunnel, the power necessary to pressurise the circuit, and the power for cooling, then

$$N_a = Nt_a + Nc_a \tag{4}$$

$$N_p = Nt_p + Np_p + Nc_p \tag{5}$$

Taking $Nt = \frac{1}{2} \rho V^3 A/\eta$, and letting $k_{1p} = Np_p/N_p$, $k_{2p} = Nc_p/N_p$, $k_{2a} = Nc_a/N_a$, and with $\rho_a/\rho_p = (P_a/P_p)(T_p/T_a)$ then

$$V_p/V_a = K\,[P_p/P_a]^{-1/3}[T_p/T_a]^{+1/3}[A_p/A_a]^{-1/3} \tag{6}$$

where $K = [(N_p/N_a)(\eta_p/\eta_a)(1-k_{1p}-k_{2p})/(1-k_{2a})]^{1/3}$

Extra power costs associated with additional tests needed to separate $R_N$ and $M_N$ effects must be assessed against the requirements for separating $R_N$ and $M_N$ effects and there may be a significant cost penalty involved.

## 2.3 Relative Performance

Taking the Reynolds number length scale as $l_m = r\,A^{\frac{1}{2}}$, commonly used in assessing tunnel performance, then the Reynolds number, Mach number, and dynamic pressure ratios for similar models tested in similar atmospheric and pressurised tunnels are given by:

$$R_{Np}/R_{Na} = K\,(P_p/P_a)^{2/3}(A_p/A_a)^{1/6}(T_p/T_a)^{-2/3}(\mu_p/\mu_a)^{-1} \tag{7}$$

$$M_{Np}/M_{Na} = K\,(P_p/P_a)^{-1/3}(A_p/A_a)^{-1/3}(T_p/T_a)^{-1/6} \tag{8}$$

$$q_p/q_a = K^2\,(P_p/P_a)^{1/3}(A_p/A_a)^{-2/3}(T_p/T_a)^{-1/3} \tag{9}$$

and the model and tunnel size ratios are given by:

$$l_{mp}/l_{ma} = w_p/w_a = h_p/h_a = (A_p/A_a)^{1/2} \tag{10}$$

These equations were derived assuming air is incompressible, and the relative performance of geometrically similar atmospheric and pressurised tunnels can be estimated after the constants have been determined.

High air temperatures can cause problems with models, parts of the circuit and the instrumentation, and additionally, the $R_N$ drops as the temperature rises (at constant power). To overcome these problems the air in the circuit is usually cooled (or an air exchanger fitted), and in the following performance comparisons it is assumed that both types of tunnel are operated at the same temperature.

## 2.4 Cost Factors

Spence and Spee's data and cost estimates from other sources indicates that $f_c \simeq 1.0$, $m_a \simeq 1.0$, and that $g_c$ depends on the fact that the tunnel can be pressurised (because of the additional items of equipment needed) and on the design pressure, and that $g_c$ can be approximated by

$$g_c \simeq 2.0 + 0.7\,[(P_p/P_a)_D - 1.0] \tag{11}$$

The value of $f_a$ depends on the maximum speed in the working section, and for a conventional tunnel design with a maximum airspeed of 130 m/s, $f_a \simeq 0.2$, and $k_{2a} \approx 0.05$. Assuming the drive and cooling system cost is directly proportional to the maximum power input, then from equations 1,4, and $Nt = \frac{1}{2}\rho A V^3/\eta$, the relations

$$f_{a_1}/f_{a_2} = (A_{a_1}/A_{a_2})\,(\rho_{a_1}/\rho_{a_2})\,(V_{a_1}/V_{a_2})^3\,((1-k_{2a_2})/(1-k_{2a_1}))(\eta_{a_2}/\eta_{a_1})(C_{a_2}/C_{a_1}) \tag{12}$$

$$(1-f_{a_1})/(1-f_{a_2}) = (C_{a_2}/C_{a_1})\,(A_{a_1}/A_{a_2})^{m_a} \tag{13}$$

enable values of $f_a$ to be calculated for different values of maximum velocity, capital cost, or size.

For the pressurised tunnel, assuming that the cost of the main drive and cooling system is also proportional to the power input, then $f_p$ is given by

$$f_p = f_a (C_a/C_p)(1-k_{1p})(N_p/N_a) \tag{14}$$

## 2.5 Efficiency, Cooling and Pressurisation Factors

If $R_{Np}/R_{Na} > 1$ the friction coefficient will be lower in the pressurised tunnel and $\eta_p/\eta_a > 1$. However, the efficiency ratio will not have a significant effect on performance and it can be taken as unity; for example, for $R_{Np}/R_{Na} \approx 2.0$ it was estimated that $\eta_p/\eta_a \simeq 1.04$ for a conventional tunnel design.

The proportion of total power required for pressurisation, $k_{1p}$, depends on the available air storage, the time allowed for pressurisation, the design pressure, and the frequency of pressurisation. It is estimated that $k_{1p} \approx 0.15$ if the compressors are operating at the same time as the main drive.

The cooling power factors $k_{2a}$ and $k_{2p}$ are small. For example, for an atmospheric tunnel with a maximum velocity of 130 m/sec and $f_a \simeq 0.20$, $k_{2a} \simeq 0.05$, and in a pressurised tunnel of the same capital cost and with the same power consumption $k_{2p} \approx k_{2a}$. To determine the cooling power factors under other conditions it may be assumed that $k_2$ is proportional to the power input.

## 3 RELATIVE REYNOLDS NUMBER, MACH NUMBER, DYNAMIC PRESSURE AND SIZE

In the following, the equations in section 2 are used to estimate relative performance for various selected capital cost and power input ratios with the constants $f_c = 1.0$, $m_a = 1.0$, $f_a = 0.2$, $k_{1p} = 0.15$, and $k_{2a} = k_{2p} = 0.05$ given previously.

### 3.1 Constant Capital Cost and Power Input

An important case for comparison is when the capital cost and power input for each tunnel are the same. This is because capital expenditure is usually limited and power costs can be a major part of the operating expense.

The $R_N$, $M_N$, and velocity ratios derived from equations 3,6,7 and 8 are plotted in figure 1 for tunnels with design pressure ratios of 2,3,4 and 5, operating at variable pressure from atmospheric to the design limit, and with a constant power input ($N_p = N_a$) and constant capital cost ($C_p = C_a$).

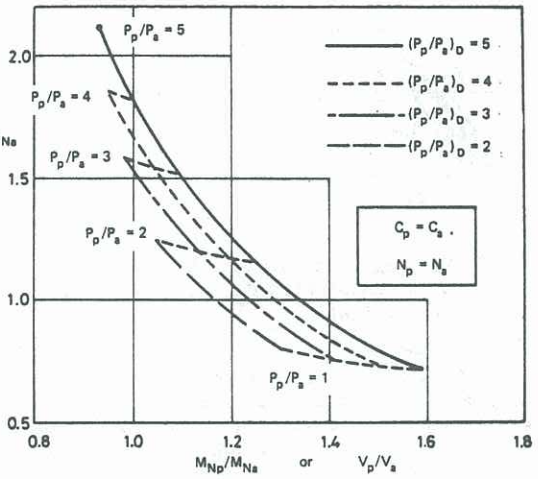

Figure 1 $R_N$, $M_N$, and velocity ratios.

Figure 1 shows that the $R_N$ and $M_N$ test capability increases significantly as the design pressure increases, and it would seem advantageous for the tunnel to have a relatively high design pressure. For example, a tunnel with $(P_p/P_a)_D = 5$ gives a maximum $R_N$ and $M_N$ test capability which is 2.1 and 1.6 times the capability of an atmospheric tunnel, but for $(P_p/P_a)_D = 3$ the maximum $R_N$ and $M_N$ fall to 1.6 and 1.4 times their values in an atmospheric tunnel.

Figure 2 shows the high dynamic pressures which can occur when operating at high pressure. For example, when operating at a design pressure ratio of 5, $q_p/q_a = 4.3$, but when operating at a lower design pressure ratio of 3, $q_p/q_a$ reduces to 2.9. High dynamic pressures can lead to very high loads on the model and cause problems in its design and support. This can be a limiting factor in the choice of design pressure.

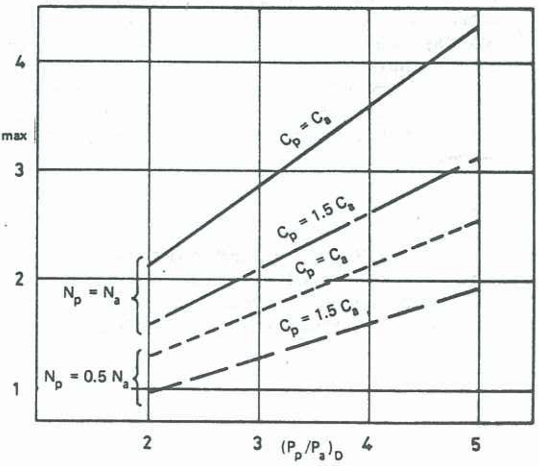

Figure 2 Maximum dynamic pressure ratios.

The working section of the pressurised tunnel is considerably smaller than the atmospheric tunnel, as shown in figure 3. For $(P_p/P_a)_D = 5$, $h_p/h_a = w_p/w_a = 0.46$, but for $(P_p/P_a)_D = 3$ this increases to 0.54. Thus, from a size point of view it is preferable to have a lower design pressure.

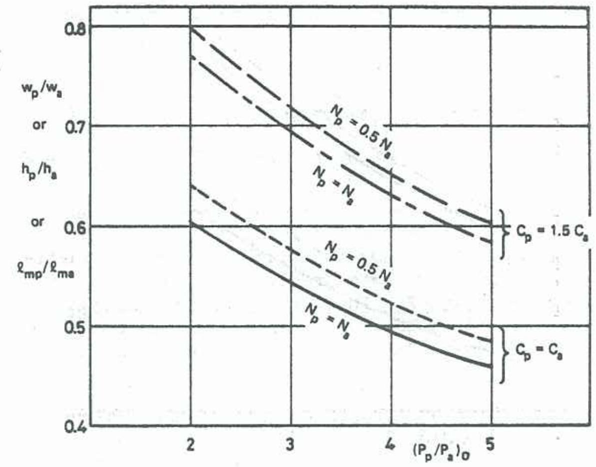

Figure 3 Tunnel working section and model size ratios

Although a constant capital cost and power input leads to a significantly higher performance, tunnel size is virtually halved. This could lead to cheaper models, but it may make it difficult to construct them with sufficient detail and it may prevent tests on some full scale objects or large scale models.

### 3.2 Other Capital Cost and Power Input Ratios

The $R_N$, $M_N$, dynamic pressure, and tunnel size ratios for three other cost and power variations, namely:

1. $C_p = C_a$, $N_p = 0.5\ N_a$
2. $C_p = 1.5\ C_a$, $N_p = N_a$
3. $C_p = 1.5\ C_a$, $N_p = 0.5\ N_a$

are shown in figures 2,3 and 4.

If the pressurised tunnel has the same capital cost as the atmospheric tunnel and a power plant with only half the maximum power of the atmospheric tunnel, then its linear dimensions can be increased by ≈7% compared with the case when $C_p = C_a$ and $N_p = N_a$, as shown in figure 3. However, an increase in the size of the working section of 7% may not alleviate the problems of model size referred to previously. Figure 4 shows that at a design pressure ratio of 4, for example, the maximum $R_N$ and $M_N$ are decreased significantly compared with the case when $C_p = C_a$ and $N_p = N_a$, although they are still appreciably greater than for the atmospheric tunnel. The dynamic pressure in the pressurised tunnel, as shown in fig. 2, is now much less than when $C_p = C_a$ and $N_p = N_a$ and little difficulty would be expected with model design or support.

If the capital cost of the pressurised tunnel is 50% greater than the atmospheric tunnel for $N_p = N_a$ or $N_p = 0.5\ N_a$ then the linear dimensions of the working section will be ≈25% larger than for the corresponding case with $C_p = C_a$ as shown in figure 3. However, a 50% increase in cost only increases the maximum $R_N$ ratio by ≈7% and decreases the maximum $M_N$ ratio by

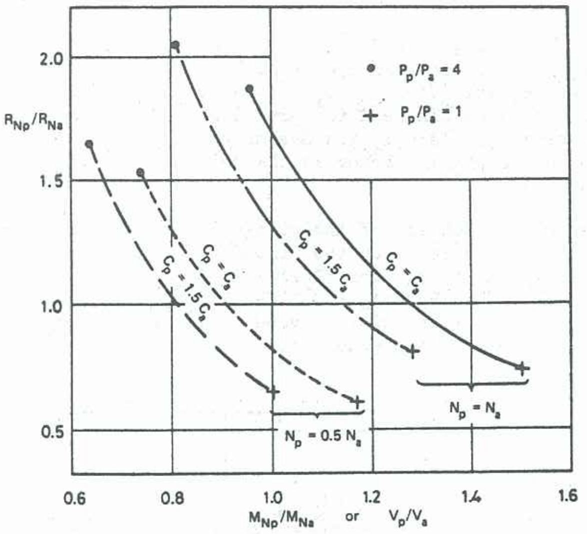

Figure 4 $R_N$, $M_N$ and velocity ratios for $(P_p/P_a)_D = 4$

≈15%, as shown in figure 4 for $(P_p/P_a)_D = 4$. Increasing the capital cost by 50% also leads to a significant reduction in dynamic pressure for the same power, as shown in figure 2. Thus, while a 50% increase in capital cost leads to a much larger tunnel it does not produce a corresponding increase in other performance parameters.

These four examples illustrate some of the options that could be explored in comparing the performance of atmospheric and pressurised tunnels. There are many others. For example, if the power for the pressurised tunnel is reduced then the power costs saved over the life of the tunnel may be offset against a similar increase in capital cost.

## 4 PRESSURISATION CONSIDERATIONS FOR A NEW AUSTRALIAN WIND TUNNEL

Recently, Lemaire, Matheson, and Thompson (1982) proposed a new atmospheric pressure low speed tunnel which will satisfy most of Australia's anticipated test requirements for perhaps the next 40 years. The layout of the tunnel follows traditional lines except that tandem working sections are specified mainly to satisfy both CTOL and V/STOL test requirements. The larger working section is 6 m x 6 m x 13.5 m, with a maximum airspeed of 60 m/s; followed by a smaller section 4.7 m x 3.4 m x 10 m, with a maximum airspeed of 135 m/s.

The analysis developed in section 2 is applied to this tunnel for the specific case of the same capital cost and power input. The $R_N$ and $M_N$ test envelope in each working section is shown in figure 5 for $(P_p/P_a)_D = 4$, together with the $R_N$ - $M_N$ limit for the atmospheric tunnel, all at a constant air temperature of 30°C. The $R_N$ is based on a length scale of $0.1(A)^{\frac{1}{2}}$. Figure 5 shows the greatly expanded test envelope for the pressurised tunnel compared with an atmospheric tunnel.

In the small working section the maximum $R_N = 6.4 \times 10^6$ and the maximum $M_N = 0.58$ compared with $R_N = 3.4 \times 10^6$ and $M_N = 0.39$ in the atmospheric tunnel. Currently, the $R_N$ sensitivity of new aerodynamic designs, particularly for high lift, appears to be increasing and this expanded $R_N$ test range can be very important. However, this advantage must be assessed against the disadvantage of reducing the size of the working sections to 3.0 m x 3.0 m and 2.3 m x 1.7 m.

Nowadays, it is recognised that as well as aiming for high test Reynolds numbers, it is also important to test models which are large enough so that full scale geometry can be faithfully reproduced, and sometimes this requires much larger models than used in the past.

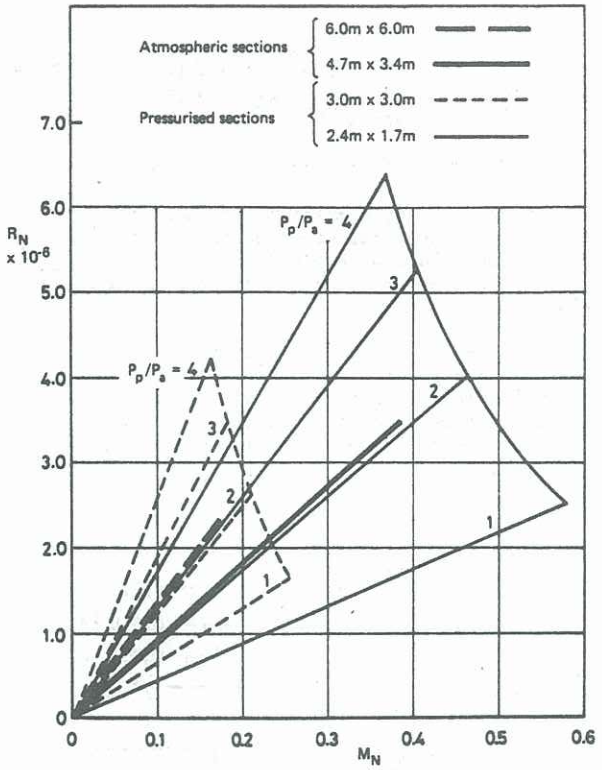

Figure 5 $R_N$ - $M_N$ test envelope for the tandem section tunnel with $C_p = C_a$, $N_p = N_a$, and $l_m = 0.1(A)^{\frac{1}{2}}$

The use of large models is especially important when testing complex high lift devices now adopted on modern aircraft. The working section must also be large enough to keep the effects of the walls within allowable limits. This usually requires a relatively large working section size to model size ratio particularly for tests of V/STOL models. The particular pressurised tunnel considered here does not satisfy the model and working section size requirements for V/STOL testing at low forward speeds. However, some investigations of CTOL and V/STOL aircraft in the high speed low specific lift regime where high test $R_N$ is the main requirement would be improved.

## 5 CONCLUDING REMARKS

The performance of low speed wind tunnels designed to operate at atmospheric pressure and at pressures between 2 and 5 atmospheres has been analysed on the basis of capital cost and power input. Both factors influence tunnel design and it is important to maximise performance for given values of these factors. For the same capital cost and power input, pressurisation allows the maximum $R_N$ and $M_N$ to be increased significantly, but the working section is much smaller. Although the increased $R_N$ and $M_N$ and the ability to separate $R_N$ and $M_N$ effects can be important the smaller working section will make it difficult to satisfy certain test requirements, particularly for V/STOL models.

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