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CONTROL OF HIGH SPEED WIND TUNNEL STAGNATION PRESSURE

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Abstract. *A simulink block diagram code was used to solve a mathematical model consisted of a set of ordinary differential and algebraic equations, which simulated a supersonic blow-down wind tunnel operation, by controlling its stagnation pressure in the settling chamber. A non-linear mathematical model was used for analyzing the open-loop system characteristics and a linearized mathematical model was obtained for the controller design. A great difficulty in supersonic blow-down wind tunnels is the undesirable variation of the Reynolds number in the test section during a tunnel run, as a consequence of the decrease in the stagnation temperature due to the adiabatic expansion in the vessel. Heat regenerators inside the storage tank, which were also modeled, were used to limit this variation. Performance of the supersonic wind tunnel using a PI (proportional-plus-integral) controller was found to be satisfactory, as confirmed by the results.*

Keywords. *Blow-down wind tunnel, Pressure Control, Temperature Control, PI controller, Simulink*

1. Introduction

This paper deals with the solution of the Reynolds number control problem in a Supersonic Wind Tunnel facility (SWT). A typical blow-down wind tunnel consists basically of a storage tank filled with high-pressure air, a convergent-divergent nozzle (CD nozzle), a test section and a diffuser. Blow-down wind tunnels require increasingly higher pressure as the Mach number increases. The pressure required to start the tunnel is experimentally found to be about twice the normal shock pressure loss, for a referenced test section Mach number. The tunnel starts with the openning of an automatic pressure regulator valve, located just after the storage tank outlet. The high-pressure air in the storage tank expands and settles down in the settling chamber, where the air is kept at a constant pressure. Downstream of the settling chamber, a CD nozzle accelerates the flow to supersonic condition up to the end ot the test section. Into the diffuser, the flow is then decelerated to near sonic condition by means of a second throat section and, finally, decelerated to atmospheric conditions by the increase ot the cross section area. A sketch of the facility is shown in Fig.1. This wind tunnel has an asymmetric sliding-block nozzle which yields a variable Mach number capability over the range of Mach number 1.5 to 4.0. Dry air is stored in a 56.6 m^3 tank at up to 2.07 MPa. Testing requirements call for regulated stagnation pressures in the range of 0.34 MPa to 1.72 MPa for typical test duration of 15 to 45 seconds. This facility is similar to the Penn State Supersonic Wind Tunnel (Fung, 1987).

At a given Mach number, it is sometimes required to maximize the test duration by running the tunnel at the lowest possible stagnation pressure – but still sufficient to maintain supersonic flow condition. Similarly, it is often necessary to obtain different Reynolds numbers at a given Mach number, by means of adjusting levels of stagnation pressure and temperature. However, a great difficulty of supersonic blow-down wind tunnels is the undesirable variation of Reynolds number in the test section during a tunnel run. This is a consequence of the stagnation temperature decrease, due to the adiabatic expansion in the vessel – heat regenerators are used to limit this variation. In all cases, a stable level of stagnation pressure and temperature during the test is the basic requirement.

The main purpose of the present work is to design and implement a controller that can sense the stagnation pressure at the settling chamber and adjust a control valve automatically in order to reach a desirable pressure level. The stagnation pressure in the settling chamber is usually controlled by one or more pressure regulator valves. The valve is opened progressively wider during a run as the storage tank pressure decreases continuously. When SWTs were first developed, they were manually operated. Since that time, many SWTs have been modified to provide better performance. Advances in microcomputers and measurement technologies have enabled operators to obtain pressures and temperatures that are more accurate, allowing SWT's control to use simpler operating system. Controller's type varies among wind tunnels depending on their size and budget. They vary from a purely mechanical controller using a set of needle valves of different diameters to a pneumatic valve with PID control (proportional-plus-integral-plus-derivative control action), Matsumoto and Wilson (2001). One of the most advances in wind tunnel operating system uses a real time neural net controller with a parallel processing workstation (Buggele and Decker, 1994). This SWT can be operated with as few as three people and has a Mach number deviation of 0.005 and total pressure deviation of 0.7 kPa (0.1 psi).

The control procedure maintains the stagnation pressure constant regardless of test section Mach number. The regulator valve is opened progressively wider during a tunnel run as the storage tank pressure continuously decreases. A satisfactory solution to this control problem has been achieved through a single-loop Proportional-plus-Integral (PI) controller with constant parameter settings.

The second purpose of this work is to present a tool to design heat regenerators in which the heat source consists of flat steel plates displaced at equal distances, Spiegel (1956). Expansion of the air from the storage tank through heat exchanger matrix (metallic flat plates) limits air temperature decay, which avoids the variation of the Reynolds number in the test section during a tunnel run.

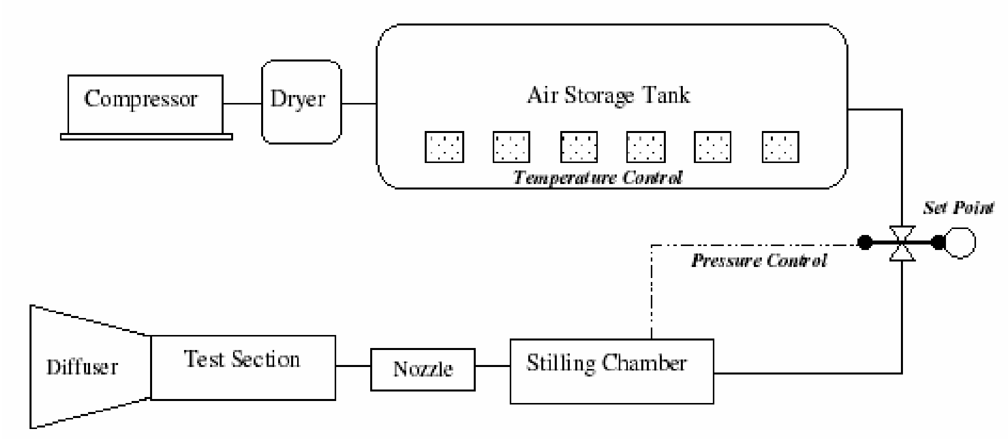

Figure 1. Schematic of supersonic wind tunnel

2. Mathematical Model

The dynamic analysis of the system SWT is divided into three modules, which are: Storage Tank, Settling Chamber and Nozzle. These modules are mathematically represented by control volumes. It is assumed that pressure, temperature and density distribution are uniform over the whole control volume during the test. Should be noted that it is assumed that all the thermodynamic processes are isentropic during the test time (no shock waves, neglect friction and heat transfer), except in the heat regenerators/tank module. The change of potential energy of the gas is small and can be neglected.

2.1. Storage tank

During a test, it is assumed that the mass influx from the compressor is negligible. Hence, the rate of decrease of mass in air tank is equal to the rate of mass efflux through the valve:

$$\frac{d\rho_t}{dt} = -\frac{1}{V_t}\dot{m}_v, \tag{1}$$

where ρ_t is the storage tank air density, $\dot{m}_v$ is the mass efflux through the valve and V_t is the storage tank volume. The subscript "t" refers to storage tank. By assuming the energy loss through the valve is negligible small, the internal energy change in the storage tank is equal to the enthalpy plus the kinetic energy through the valve. Therefore:

$$\frac{dU_t}{dt} = -\dot{m}_v h_v - \frac{1}{2}\dot{m}_v v_v^2, \tag{2}$$

where U_t is the storage tank air internal energy, h_v is the specific enthalpy of the air through the valve and v_v is the velocity of the air through the valve. In terms of the pressure, the Eq. (2) can be written (Fung, 1987):

$$\frac{dP_t}{dt} = -\left(\frac{c_p}{c_v}\frac{R}{V_t}\right)\dot{m}_v T_t \cdot \tag{3}$$

The quotient $\gamma = c_p / c_v$ is the specific heat ratio and R is the gas constant.

The valve characteristics are described in Fisher Controls Company (1984), from the manufacturer. The mass flow at different valve positions is given by:

$$\dot{m}_v = \frac{2.2958x10^{-8}}{\sqrt{T_t}} C_g P_t \sin\left(2.71\sqrt{\frac{\Delta P}{P_t}}\right) \cdot \tag{4}$$

where C_g is the "gas sizing coefficient" of the valve. Table 1 shows some characteristic values in the valve operating range. The variables T_t and P_t are the thermodynamics properties (temperature and pressure) of the air into storage tank. ΔP is the pressure difference across the valve. It is assumed that $\Delta P = P_t - P_0$, where P_0 is the stagnation pressure at the settling chamber.

Table 1 – The gas sizing coefficient of the valve

θ	0	10	20	30	40	50	60	70	80	90
C_g	0	194	1680	3767	6230	9288	12835	16351	18942	23120

2.2. Settling Chamber

The second control volume is the settling chamber as shown in Fig. 1. Air flows into the settling chamber from the control valve and goes through the CD nozzle to the test section. Therefore, the mass flow difference rate from inlet and outlet section of the control volume yields the net rate of mass buildup inside the control volume. In other words, the relation of mass conservation in the settling chamber is given by:

$$\frac{d\rho_0}{dt} = \frac{1}{V_0}\left(\dot{m}_v - \dot{m}_*\right) \cdot \tag{5}$$

Subscript "0" refers to the settling chamber and subscript "*" refers to mass flow rate through the nozzle. The energy entering the settling chamber volume with mass flow $\dot{m}_v$ minus the energy exiting through the nozzle with mass flow $\dot{m}_*$ is equal to the internal energy rate in the settling chamber. Therefore, the relation of conservation of energy for the settling chamber is:

$$\frac{dU_0}{dt} = \dot{m}_v h_v + \frac{1}{2}\dot{m}_v v_v^2 - \dot{m}_* h_* + \frac{1}{2}\dot{m}_* v_*^2 \cdot \tag{6}$$

Rewriting the Eq.(6) in terms of pressure, results (Fung, 1987):

$$\frac{dP_0}{dt} = \left(\frac{c_p}{c_v}\frac{R}{V_0}\right)\left(\dot{m}_v T_t - \dot{m}_* T_0\right) \cdot \tag{7}$$

2.3. Nozzle

The nozzle of the supersonic wind tunnel is asymmetric, variable-geometry with converging-diverging geometry. Sliding the lower block changes the test section Mach number. It is assumed that the flow from the settling chamber to the test section runs an isentropic process. Considering the air as a perfect gas and the stagnation state as the reference state, it can be written $\dot{m}_*$ as function of stagnation pressure and the nozzle throat area A_*, which are:

$$\dot{m}_* = \frac{0.6847 P_0 A_*}{\sqrt{R T_0}}, \tag{8}$$

where

$$\frac{A}{A_*} = \frac{1}{Mach}\left\{\frac{1+\left[\gamma-1/2\right]Mach^2}{\left[\gamma+1/2\right]}\right\}^{\frac{\gamma+1}{[2(\gamma-1)]}}. \tag{9}$$

3. Control Problem

The primary reason for installing a good controller to a wind tunnel is to significantly improve flow quality in the test section. The required flow steadiness may vary with the type of tunnel. For a typical airplane test, criteria such as less than 1.0 percent of error in *Cd* and *Cp* are usually sufficient. To meet those criteria, the Mach number steadiness in the test section must stay about ± 0.3 percent at $M = 3.0$ (Marvin, 1987). Unlike Mach number, it is hard to maintain Reynolds number at a constant value since the temperature of the storage tank drops during a test.

The present pressure control problem is relatively simple once only accuracy and stability are matters of prime concern. Then it was judged that the complexities of optimal control, neural networks and so on, are neither needed nor desired for present purposes. Besides that, the variation of the air temperature into the test section can be satisfactorily reduced with the aid of heat regenerators.

3.1. Stagnation pressure in storage tank

The objective in setting up the controller parameters for the valve is to minimize the initial transient duration to obtain as long steady run time as possible. The control process needs a model of the pressure transmitter, the digital valve controller and the automatic ball valve to perform the SWT's control. The stagnation pressure in the settling chamber is converted to current signal by a pressure transmitter located upstream the nozzle. Then this signal feeds the digital valve controller. The controller has two parameters that can be changed to maintain a steady settling pressure, a proportional gain (K_p) and an integral time (K_i). The digital valve controller compares the stagnation pressure with a set pressure and derives a corrective output signal according to the setting of its two parameters. These parameters may be modified to increase the process performance. The transfer function of the PI controller is:

$$G(s) = \frac{\Theta(s)}{E(s)} = K_p\left(1+\frac{1}{K_i s}\right), \tag{10}$$

where $\Theta(s)$ is the valve opening position and $E(s) = P_d - P_0(s)$ is the error signal between the reference input P_d (desired stagnation pressure), and the system output $P_0(s)$ (the actual pressure measured into the settling chamber). Applying the inverse Laplace transform, the differential relationship between the input $E(t) = P_d - P_0(t)$ and output $\Theta(t)$ of the PI controller is:

$$\frac{d\Theta(t)}{dt} = -K_p\frac{dP_o(t)}{dt} + \frac{K_p}{K_i}\left(P_d - P_0(t)\right). \tag{11}$$

3.2. Stagnation temperature in storage tank

The stagnation temperature control problem was solved using heat regenerators. The heat source consists of a beam of flat steel plates equally displaced. The working air flows through the space between these plates. In order to reduce the number of independent variables that must be considered in the analysis, an assumption was made that the heat conduction along the plates can be neglected. Furthermore it will be assumed that changes in density and thermal constants with the temperature may be neglected. Denoting the air temperature by T_t and the steel temperature by T_s the amount of heat transferred per unit time and per unit area of the plates can be expressed by the formula (Spiegel, 1956):

$$q = h(T_s - T_t), \tag{12}$$

where h is the heat transfer coefficient between the plates and the air. Therefore, the relation of conservation of energy for the heat regenerators is given as:

where *h* is the heat transfer coefficient between the plates and the air. Therefore, the relation of conservation of energy for the heat regenerators is given by:

$$\begin{cases} Sq = -Mc_s \dfrac{dT_s}{dt} \\ Sq = Nc_p \dfrac{dT_t}{dt} \end{cases}. \tag{13}$$

In these expressions *M* represents the mass of the steel plates in the regenerator, *N* is the mass of the air in the regenerator at the time *t*, *S* the total plate area (for every plate both sides are taken), c_s and c_p are the specific heats of steel and air, respectively. The term $\dfrac{d(\ )}{dt} = \dfrac{\partial(\ )}{\partial t} + u\dfrac{\partial(\ )}{\partial x}$ represent the substantive derivative, where u is the velocity in axial direction.

Consider the time that an air particle passed in the regenerator. With moderate air velocity, this time will be very short compared with the tunnel running time. During this short time, the air temperature at a fixed position *x* in the regenerator changes very little as a consequence of the slow variation in the air temperature entering in each station of the regenerator. On ground of these considerations, the term $\dfrac{\partial T_t}{\partial t}$ can be neglected. As it has been said previously, the heat conduction along the plates can be neglected, and this results that $\dfrac{\partial T_s}{\partial x} = 0$. The system of differential equation can now be approximated to:

$$\begin{cases} -Mc_s \dfrac{\partial T_s}{\partial t} = Sh(T_s - T_t) \\ Nc_p \dfrac{\partial T_t}{\partial x} = Sh(T_s - T_t) \end{cases}. \tag{14}$$

For the determination of the heat transfer coefficient use will be made of Reynolds formulation of the analogy between heat transfer and skin friction, which can ultimately be expressed by the formula (Spiegel, 1956):

$$h = \frac{1}{2}\rho_t c_a w C_f \, . \tag{15}$$

where C_f is the coefficient of skin friction, C_a is the specific heat of the air and $\rho_t w$ is the product of air density by air velocity in heat regenerator.

In order to solve this system of partial differential equations certain boundary conditions must be given. Initially the steel temperature T_s has the same value as the air temperature in the storage tank, thus, at *t* = 0 s holds:

$$T_t = T_s = T_{amb} \qquad in \qquad t = 0 \, . \tag{16}$$

The second boundary condition can be found by considering the air temperature at the inlet of the regenerator during the tunnel operation (Spiegel, 1956). Since the pressure and temperature variation in the test section is small during a test, it may be assumed, that the air used during the test is removed from the air tank at a constant rate ($\dot{r}$). The relation between the initial mass of air in the tank (G_0) and the mass (G) at any time *t* during the test can thus be written:

$$G = G_0\left(1 - \frac{\dot{r}\ t}{G_0}\right). \tag{17}$$

In terms of the air density (ρ), this relation can be given in the form:

$$\rho_t = \rho_{init}\left(1-\frac{\dot{r}\,t}{G_0}\right). \tag{18}$$

As the air is flowing out of the tank at constant rate, it is clear that the ratio $\frac{G_0}{\dot{r}}$ can be interpreted as the time (t_m) in which the tank would be empty. Assuming that the air in the tank is expanded isentropically during operation of the tunnel, it can be easily deduced that the air temperature in the tank is related to the parameter $\tau = \frac{t}{t_m}$ by the formula:

$$T_{inlet\_t} = T_{init}\left(1-\tau\right)^{\gamma-1}, \tag{19}$$

where T_{inlet_t} is the air temperature into the tank, before the heat regenerators, at a given time *t*.

4. Numerical Implementation

From the preceding discussion, expressions were obtained which describe the behavior of the SWT and the control systems. These are summarized here:

- Supersonic Wind Tunnel:

Storage Tank:

$$\frac{d\rho_t}{dt} = -\frac{1}{V_t}\dot{m}_v, \tag{1}$$

$$\frac{dP_t}{dt} = -\left(\frac{c_p}{c_v}\frac{R}{V_t}\right)\dot{m}_v T_t. \tag{3}$$

Settling Chamber:

$$\frac{d\rho_0}{dt} = \frac{1}{V_0}\left(\dot{m}_v - \dot{m}_*\right). \tag{5}$$

$$\frac{dP_0}{dt} = \left(\frac{c_p}{c_v}\frac{R}{V_0}\right)\left(\dot{m}_v T_t - \dot{m}_* T_0\right). \tag{7}$$

Valve:

$$\dot{m}_v = \frac{2.2958x10^{-8}}{\sqrt{T_t}} C_g P_t \sin\left(2.71\sqrt{\frac{\Delta P}{P_t}}\right). \tag{4}$$

Control Valve:

$$\dot{m}_v = \frac{2.2958x10^{-8}}{\sqrt{T_t}} C_g P_t \sin\left(2.71\sqrt{\frac{\Delta P}{P_t}}\right). \tag{4}$$

Nozzle:

$$\dot{m}_* = \frac{0.6847 P_0 A_*}{\sqrt{RT_0}}. \tag{8}$$

- Control devices:

Valve Angle:

$$\frac{d\Theta(t)}{dt} = -K_p\frac{dP_o(t)}{dt} + \frac{K_p}{K_i}\left(P_d - P_0(t)\right), \tag{11}$$

Heat Regenerator:

$$\begin{cases} -Mc_s\dfrac{\partial T_s}{\partial t} = Sh\left(T_s - T_t\right) \\ Nc_p\dfrac{\partial T_t}{\partial x} = Sh\left(T_s - T_t\right) \end{cases}. \tag{14}$$

The above equations become a system of five first-order nonlinear differential equations, in the time, with five state variables: P_t, ρ_t, P_0, ρ_0, T_s. The inputs of this system are: test section Mach number, which results in a determined nozzle geometry; the valve position $\Theta(C_g)$, which determines the control valve behavior, according to changes in C_g; the air temperature into the storage tank before the heat regenerators T_{inlet_t}, which give us the boundary conditions for determination of storage tank temperature (T_t). The output of this system are the stagnation pressure (P_0) and temperature (T_0) in the settling chamber.

Figures 2 and 3 show schematic blocks diagrams regarding the SWT model (control pressure and controller), making use of a graphical editor of the MATLAB-Simulink package (The Mathworks, 2002). Figure 4 presents a general block diagram (for the whole wind tunnel) that includes the former ones. It illustrates the data loading, input signals and taking out the results.

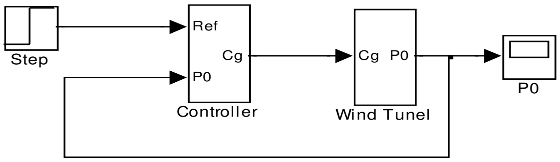

Figure 2. Block diagram: Control Pressure

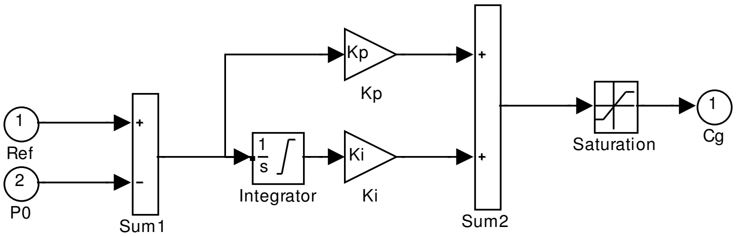

Figure 3. Block diagram: Controller

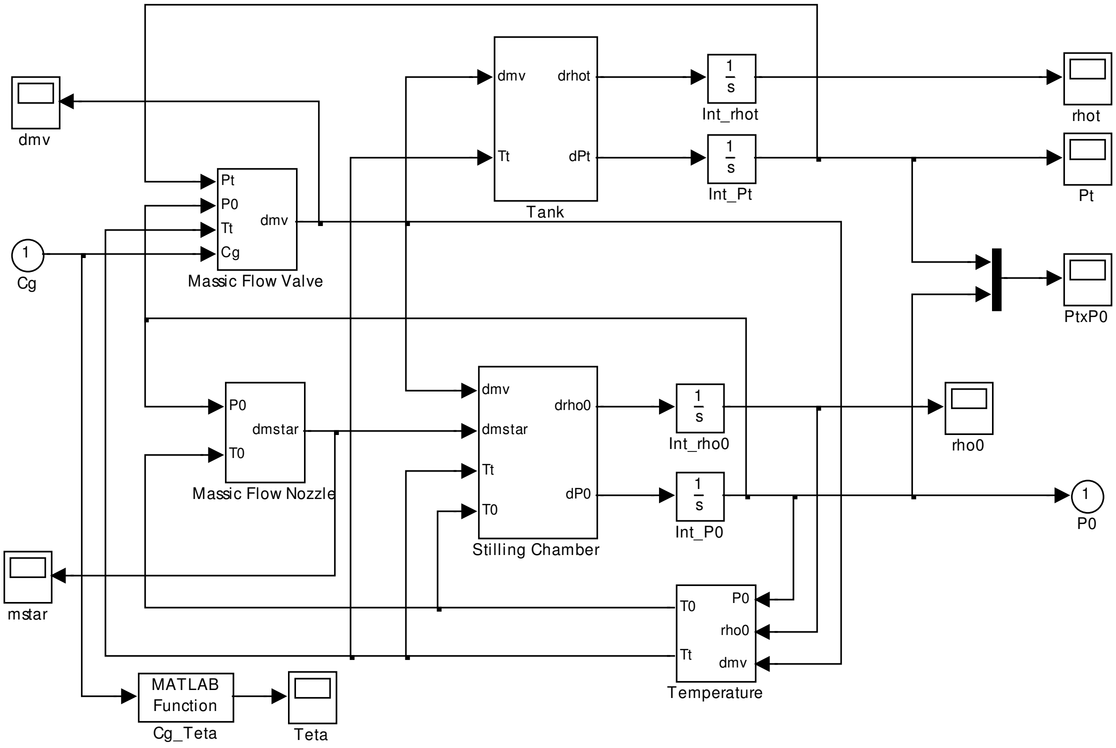

Figure 4. Block diagram: Wind Tunnel

Consider once more the system of differential equations (14). If one substitutes the derivatives by their linear differences, the system becomes:

$$\begin{cases} T_s(x,t+\Delta t) = T_s(x,t)+\beta\,\Delta t\,[T_s(x,t)-T_t(x,t)] \\ T_t(x+\Delta x,t) = T_t(x,t)+\alpha\,\Delta x\,[T_s(x,t)-T_t(x,t)] \end{cases}. \tag{20}$$

The parameters of heat transfer α and β are defined by:

$$\alpha = \frac{C_f L}{\delta}, \tag{21}$$

$$\beta = \frac{-(\rho_t w)\, C_a C_f t_m}{C_m\, \varepsilon e}, \tag{22}$$

where C_m and ε area the specific heat and specific weight of the steel, respectively. The geometric parameter δ is the distance between the flat plates, L is the length of the regenerator, the parameter e is the plate thickness. The quantity t_m, as previously defined, is the ratio between the initial air mass in the tank and the mass flow (the quantity being transported) ($\dot{r}$). In this approximation, the variable t_m was defined constant during all the simulation, i. e., $\dot{r} = const$.

5. Results

5. 1. Configuration of the Simulation

Tunnel run time depends on the kind of tests are to be made and also on their particularities. In pressure tests, for example, several pressure orifices are normally installed at various locations in the surface of the wind tunnel model. Connections are made to these orifices with flexible tubes that go outside of the tunnel. Then, the tubes are connected to pressure-measuring devices from which the pressures are recorded. In this type of test, a significant amount of time is usually required in order to stabilize the pressure at the measuring device, particularly if the passage orifice diameters are of small size. The tubes are normally quite small and causes high resistance to air flow. As the pressure at the orifice and at the measuring device approach each other, the pressure differential decreases, with the result that the measured pressure approaches the orifice pressure asymptotically. In a blow-down wind tunnel it would be unwise to depend on pressure stabilization in less than 15 or 20 seconds with a system of the type described. This is an important factor in specifying run-time requirements. Of course, with large model, and pressure transducers located very near the orifices, within the model, a much faster response can be obtained (Pope, 1965). Because of the data recording times required for force and pressure tests, and the time for the pressure control valve to provide a stable operating pressure, blow-down wind tunnels are usually designed for **minimum run** times of **20 to 40 seconds** (Pope, 1965). In order to satisfy this requirement for the present facility, adequate initial conditions were stablished, as shown in Tab.2.

By adding a controller in a feedback loop to the wind tunnel plant (Figure 2), the mathematical model for the closed-loop system is established. The result settings for the control parameters K_p and K_i are presented in Tab. 3. The wind tunnel geometrical design parameters considered herein are shown in Table 4. Table 5 shows the heat transfer parameters used in the heat regenerator design. Here the parameters α and β had been chosen based on other similar cases, just for academic reasons. It does not objective in this work to design a heat regenerator for this tunnel, in particular. The primary reason here is to offer a mathematical tool for the stagnation temperature control in the settling chamber.

Table 2 – Initial and **desired** conditions

T_t [K]	P_t [Pa]	T_0 [K]	P_0 [Pa]	**Pressure (Set Point) [Pa]**	**Mach (Test Section)**
298	$1.8\ 10^6$	298	$1.01\ 10^5$	**$5.\ 10^5$**	**2.5**

Table 3 – Parameters of the pressure controller

K_p	K_i
0.5	1.5

Table 4 – Geometric configuration of SWT

V_t [m^3]	V_0 [m^3]	A (Test Section) [cm^2]	A* (Nozzle) [cm^2]
56.61	$V_t/20$	15x18	0.0102

Table 5 – Parameters of the heat regenerator

α	β
3.	-3.

5. 2. SWT without Control

In order to judge the accuracy and efficacy of the mathematical model, experimental (Fung, 1987) and simulation results for the stagnation pressure, when the tunnel is running at Mach number 4.0, were compared with the valve fully opened condition. The initial pressure of the storage tank is 1.8 MPa. It is important to note that blow-down wind tunnels, invariably, must essentially operate at a constant pressure level during each run. However, in accordance with the Figs. 5 and 6, the pressure did not remain constant in the settling chamber. Additionally it is also observed that there was a significant fall in the temperature. Therefore, it can be concluded that control systems for pressure and temperature are both essential for this facility.

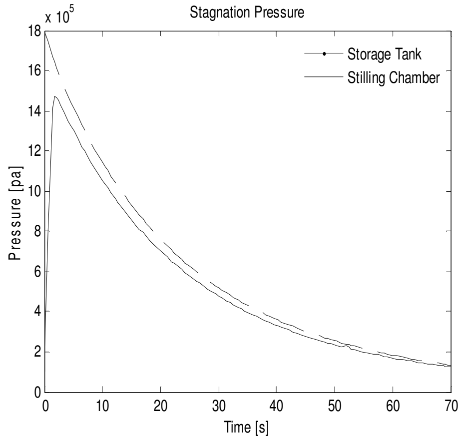

Figure 5. Variation in stagnation pressure (valve fully open)

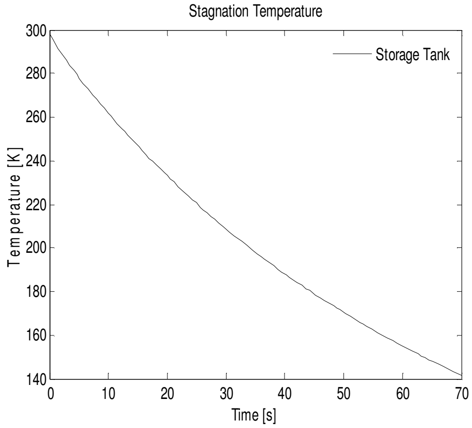

Figure 6. Variation in stagnation temperature (valve fully open)

5. 3. SWT with Pressure Control

At a given test section Mach number it is desirable to maintain steady-state condition for the stagnation pressure in the settling chamber, as long as possible, to obtain the maximum span of test time. Since the pressure in the tank continuously decreases during the test, the valve opening should be gradually increased for maintaining constant stagnation pressure. In this particular case, only the pressure control was operational – no heat regenerator into the tank was considered. Figures 7 and 8 show that the mathematical model used in the simulation could successfully capture this behavior. Although the pressure has been controlled, the temperature in the settling chamber has fallen significantly (see Fig. 9). This temperature decay caused a significant variation in test section Reynolds number during the tunnel run. Thus, considering the geometric and thermodynamic parameters adopted for the tunnel, one can conclude that it is very convenient the use of heat regenerators in the storage tank.

For a determined Mach number, each stagnation pressure value gives a different Reynolds number in the test section. To obtain a response with a minimum steady-state error and overshoot, as well as fastest settling time, the controller parameters K_p and K_i must be adjusted. One aim of this work is, basically, to provide a range of controller parameters that could reasonably be implemented – avoiding too many experimental runs to determine these parameters on a trial-and-error basis. It can be observed in Fig. 8 that, with exception of the initial transient period, the derivative changes of the opening angle valve are very smooth. Therefore, for this test configuration (size of storage tank, test section Mach number and so on), the pressure regulator valve can be manually adjusted. It was worth noting here that numerical simulations are essential for the decision on project parameter such as, for example, the size of the air storage tanks.

It is also observed that the pressure control system allowed a longer high temperature level in the storage tank. This behavior is evidenced when compared the derivatives of stagnation temperature in Figs. 6 and 9.

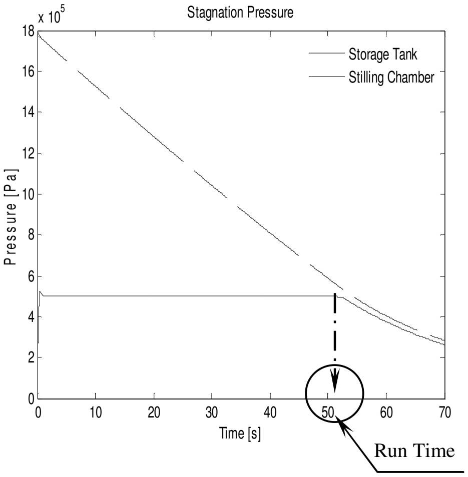

Figure 7. Variation in stagnation pressure (Pressure Control)

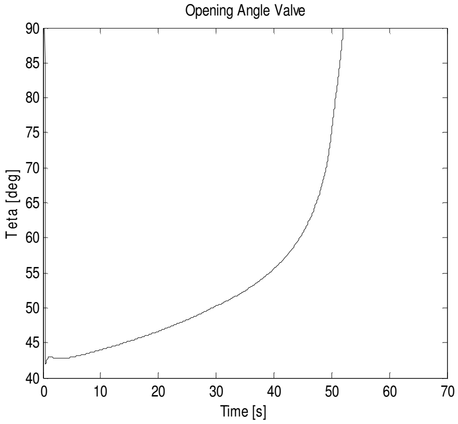

Figure 8. Variation in valve opening angle (Pressure Control)

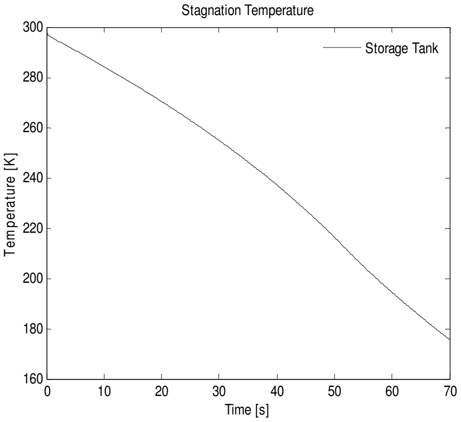

Figure 9. Variation in stagnation temperature (Pressure Control)

5. 4. SWT with Pressure and Temperature Control

Achieving constant stagnation pressure is a critical concern for SWT testing. However, it is not sufficient to comply with the requirements of flow accuracy in test section. It is also necessary a stagnation temperature control. The previously noted decrease in air stagnation temperature during a test run is due to the expansion of the remaining air in the tank, to a lower pressure, once part of the air in the tanks was removed to run the tunnel. The expansion of the air in the tank does not follow an adiabatic process, because while the air temperature in the tank drops, heat is transferred from the tank walls to the air. This result in a polytropic expansion process with a polytropic exponent of expansion process n between 1.0 (isothermal process) and 1.4 (adiabatic process) in the equation (Pope, 1965):

$$\frac{T_t^i}{T_t^f} = \left(\frac{P_t^i}{P_t^f}\right)^{\frac{n-1}{n}}, \tag{23}$$

where the subscript "*i*" refers to initial condition and "*f*" to final condition in the storage tank. This drop in stagnation temperature inside of the storage tank can become a real trouble. It affects the test section Mach number and Reynolds number during a test run. Some effort is therefore justified to reduce this temperature drop or perhaps completely nullify it. In Figs. 10 to 12 are depicted the stagnation pressure variation, valve opening angle and stagnation temperature with the time, respectively. During these tests the controller parameters K_p and K_i had not been modified. On the basis of Fig. 11, it can be concluded that it is necessary a light adjust in controller parameters K_p and K_i, in view of the oscillatory character observed. In certain cases, this implementation is of basic importance since it influences directly in the mass flow through the valve and, as a consequence, in run time of SWT (Figures 7 and 10).

It can be observed that the linearized mathematical model used to control the stagnation pressure was also found to be satisfactory (see Fig.10). In this particular simulation, with pressure and temperature controls, the polytropic exponent (n_{TP}) was 1.0002 – the physically possible expected range is $1. < n_{TP} < 1.4$. As the polytropic exponent is very near to isothermal process, it can be concluded that the heat regenerators are too large for this facility.

In the other hand, the polytropic coefficient calculated from the simulation with only the pressure control (n_P) (last case) was 1.39. The physical expected value would be 1.40 once no heat transfer was considered during the simulation. However, it is worth noting that the Eq. (23) is applied to a quasi-static process, derived from a steady-state approximation of Bernoulli equation and, of course, some approximation errors may be expected. In this context, the value $n_P = 1.39$ is consistent with the formulation adopted and a good physical approximation.

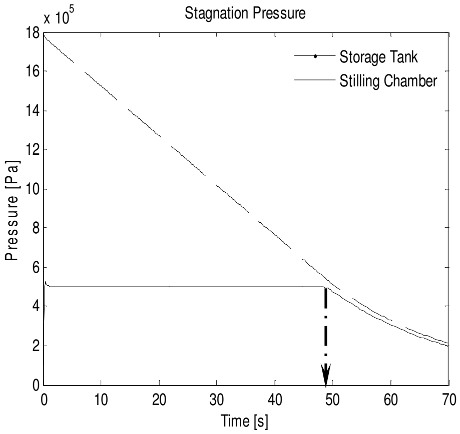

Figure 10. Variation in stagnation pressure (Pressure and Temperature Control)

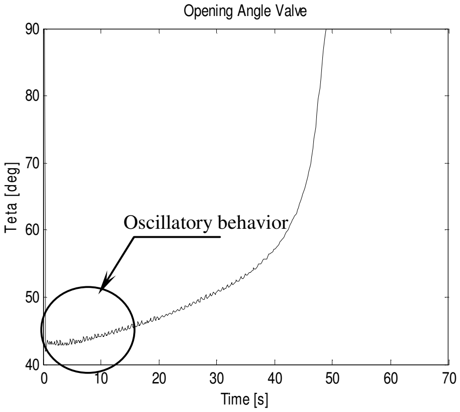

Figure 11. Variation in valve opening angle (Pressure and Temperature Control)

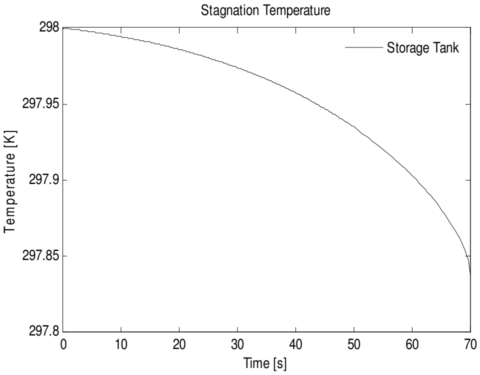

Figure 12. Variation in stagnation temperature (Pressure and Temperature Control)

6. Conclusions

This research deals with the solution of the stagnation pressure control problem using a PI controller in a supersonic wind tunnel. The objective is to provide a controlled airstream, in terms of temperature and pressure, so that, items of interest to aeronautical engineers can be tested. The simulink block diagram code was used to solve a model consisted of a set of ordinary differential and algebraic equations to control the stagnation pressure inside a supersonic blow-down wind tunnel. A great difficulty in supersonic blow-down tunnels is the undesirable variation of the Reynolds number in the test section during a test run as a consequence of the decrease in stagnation temperature due to the adiabatic expansion into the vessel. In order to limit this variation, it was used heat regenerators. Performance of the supersonic wind tunnel using a PI controller together with heat regenerator models was found to be satisfactory.

The required flow accuracy may vary with the type of tunnel. Most of recent systems developed are based on real-time controllers. Generally, a real-time feedback loop such as a proportional-plus-integral-plus-derivative (PID) controller works very well with long-duration wind tunnels. For this case, the storage air pressure decreases slowly enough to allow devices with slow time response to have sufficient time to respond to the pressure change. However, when the storage volume is limited, a real-time loop may fail to keep up with the fast pressure decay. In addition, very small time delays due to the motion of the mechanical elements of a valve become critical. Under such circumstances, alternative approaches, such as neural networks may be needed. A pre-programmed controller is proposed as a simple alternative to a neural net controller to achieve a fast responding system. It offers the capability of starting the wind tunnel very quickly and providing a stable flow, overcoming the slow response of a PID controller. Therefore, just after investigating different control algorithms it will be possible to estimate performance parameters for different classes of SWT.

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