

NUMERICAL AND EXPERIMENTAL INVESTIGATION OF DIRECT
CONNECTED RAMJET TEST FACILITY

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
MECHANICAL ENGINEERING

SEPTEMBER 2014

Approval of the thesis:

**NUMERICAL AND EXPERIMENTAL INVESTIGATION OF DIRECT
CONNECTED RAMJET TEST FACILITY**

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ABSTRACT

NUMERICAL AND EXPERIMENTAL INVESTIGATION OF DIRECT CONNECTED RAMJET TEST FACILITY

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September 2014, 98 pages

The main objective of this study is to make a numerical model of direct connected ramjet test facility which is used for ground tests of supersonic air breathing propulsion systems. Conceptual design of a direct connected ramjet test facility is performed. 1 dimensional transient numerical model is made according to this conceptual design. Numerical model is made by using 1 dimensional computational fluid dynamic code FLOWNEX. Validation of the numerical model is performed by comparison of test data. After the validation, numerical model is used to analyze the test facility dynamics and the design parameters. A procedure is developed to generate a test condition of a ramjet engine. This procedure is used to create a flight condition and a ramjet engine is tested on the numerical model.

Keywords: Air Breathing Propulsion Systems, Ramjet Test Facility, Direct Connected Test Facility

ÖZ

BORU BAĞLANTILI RAMJET TEST DÜZENEĞİNİN NÜMERİK VE DENEYSEL İNCELENMESİ

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Şubat 2014, 98 sayfa

Bu çalışmanın temel amacı hava solunmalı itki sistemlerinin yer seviyesi testlerinde kullanılan boru bağlantılı test düzeneklerinin modellenmesini yapmaktır. Tez kapsamında boru bağlantılı ramjet test düzeneğinin kavramsal tasarımı yapılmıştır. Kavramsal tasarım baz alınarak zamana bağlı bir boyutlu nümerik model oluşturulmuştur. Nümerik modelin oluşturulmasında bir boyutlu hesaplamalı akışkanlar dinamiği programı FLOWNEX kullanılmıştır. Doğrulama işlemi test sonuçları ile kıyaslanarak yapılmıştır. Doğruluğu tamamlanan nümerik model kullanılarak, test düzeneğinin dinamikleri ve tasarım parametreleri incelenmiştir. Nümerik model kullanılarak bir ramjet motorunun uçuş benzeşimi için gerekli koşulların test düzeneğinde sağlanabilmesi için bir test prosedürü geliştirilmiştir. Bu prosedür kullanılarak test koşulu oluşturulmuş ve nümerik model üzerinde ramjet motoru test edilmiştir.

Anahtar Kelimeler: Hava Solunmalı İtki Sistemleri, Ramjet Test Düzeneği, Boru Bağlantılı Test Düzeneği

To my family

ACKNOWLEDGEMENTS

Firstly, I would like to express my deepest appreciation to my supervisor Prof. Dr. M. Haluk AKSEL, Dr. K. Atilgan TOKER and Dr. M. Ali Ak for their guidance, advice, and support.

I especially would like to thank my colleague Murat BAYRAMOGLU, Utku OLGUN and Umit POYRAZ for their support. I performed the firing tests by being a part of this great and highly motivated team.

I would like to thank my family for their support and encouragement through my whole life.

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LIST OF SYMBOLS

SYMBOLS

p	Pressure
T	Temperature
ρ	Density
M	Mach Number
Q	Heat Transfer
h	Convection Coefficient
k	Conduction Coefficient
Nu	Nusselt Number
Nu	Prandtl Number
p_{rc}	Pressure Recovery Factor
C_v	Flow Coefficient
F_N	Thrust
\dot{m}	Mass Flow Rate
V	Velocity
A	Area
γ	Specific Heat Ratios
R	Gas Constant
q	Volumetric Flow Rate
S_g	Specific Gravity of a Gas Relatively To Air
x	Pressure Drop Ratio
Y	Expansion Ratio
P	Power
C_p	Specific Heat at Constant Pressure
F	Friction Factor
L	Length

D	Diameter
R	Radius
K	Loss Coefficient
ϕ	Equivalence Ratio
C_d	Discharge Coefficient

LIST OF ABBREVIATIONS

ABBREVIATIONS

DCSCTF	Direct-Connect Supersonic Combustion Test Facility
CHSTF	Combustion Heated Scramjet Test Facility
AHSTF	Arc-Heated Scramjet Test Facility
CARS	Raman Spectroscopy
CEA2	the Gordon-McBride program

CHAPTER 1

INTRODUCTION

In the early, 1900's some of the original ideas concerning ramjet propulsion were first developed in Europe. Thrust is produced by passing the hot exhaust from the combustion of fuel through a nozzle. The nozzle accelerates the flow and the reaction to this acceleration produces thrust. To maintain the flow through the nozzle, the combustion must occur at a pressure that is higher than the pressure at the nozzle exit. In a ramjet, the high pressure is produced by "ramming" external air into the combustor using the forward speed of the vehicle. In a turbojet engine, the high pressure in the combustor is generated by a compressor. But there are no compressors in a ramjet. Therefore, ramjets are lighter and simpler than a turbojet. The combustion that produces thrust in the ramjet occurs at a subsonic speed in the combustor. For a vehicle traveling supersonically, the air entering the engine must be slowed to subsonic speeds by the aircraft inlet. Shock waves present in the inlet cause performance losses for the propulsion system.

Ramjets produce thrust only when the vehicle is already moving; ramjets cannot produce thrust when the engine is stationary or static. Since a ramjet cannot produce static thrust, some other propulsion system must be used to accelerate the vehicle to a speed where the ramjet begins to produce thrust. Similarly, ramjets cannot be tested statically like solid propellant rocket motors. A facility (like a wind tunnel) is needed to supply air to the air intake. This air is important to simulate the flight conditions of the ramjets. Mostly two different kinds of test facilities are used according to the test requirements. Direct Connected Test Facility and Semi-Free/Quasi-Free/Free Jet Test Facilities are used to observe the sub-systems such as combustion chamber, air intake performance or the whole engine.

1.1 RAMJET TEST TECHNIQUES

A generic ramjet engine is given in Figure 1.1 schematically. This notation is taken from reference [1]. Station 0 describes the free stream conditions. Free stream condition depends on the flight condition; pressure is 1 atm and temperature is 273.15K for sea level. Station 1 is the inlet condition of air intake. Static pressure and temperature is the same as the station 0 but the total values (total temperature and total pressure) depend on the velocity of the ramjet. These values can be found by using the following isentropic relations.

$$p_t = p(1 + 0.5(\gamma - 1)M^2)^{\frac{\gamma}{\gamma-1}} \quad (1.1)$$

$$T_t = T(1 + 0.5(\gamma - 1)M^2) \quad (1.2)$$

Where p is the pressure, T is the temperature, M is the Mach number and γ is the specific heat ratio. The subscript t indicates the stagnation conditions.

Station 2 is the exit of the air intake. Flow is supersonic at station 1 however at station 2 flow is subsonic and static pressure and temperature are higher. This transition is due to oblique and normal shock wave system in the air intake.

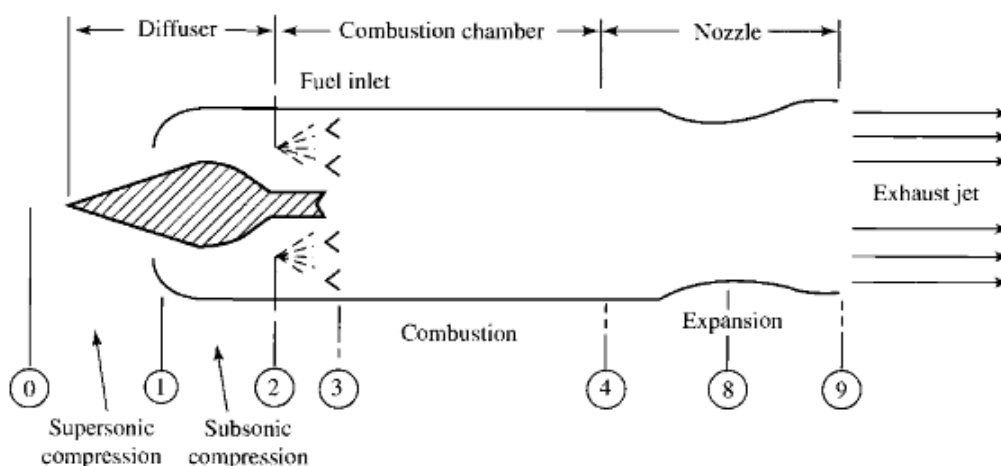


Figure 1.1 Ramjet Engine Station Nomenclature

An air intake is given in Figure 1.2. Oblique and normal shock waves work as a compressor of a turbojet engine to increasing the pressure of the air. These shock waves reduce the total pressure of the air. This reduction is defined as pressure recovery. This parameter defines the efficiency of the air intake.

$$p_{rc} = p_{t2}/p_{t1} \quad (1.3)$$

p_{rc} is the pressure recovery factor. The subscripts $t1$ and $t2$ indicates the stagnation conditions of the corresponding station number which is mentioned in Figure 1.1.

Ramjet has two components which have great influence on each other. These are the air intake and combustion chamber. The performances of air intake and combustion chamber are coupled to each other. For this reason, air intake and combustion chamber are tested separately at the initial phase and later the whole ramjet is tested.

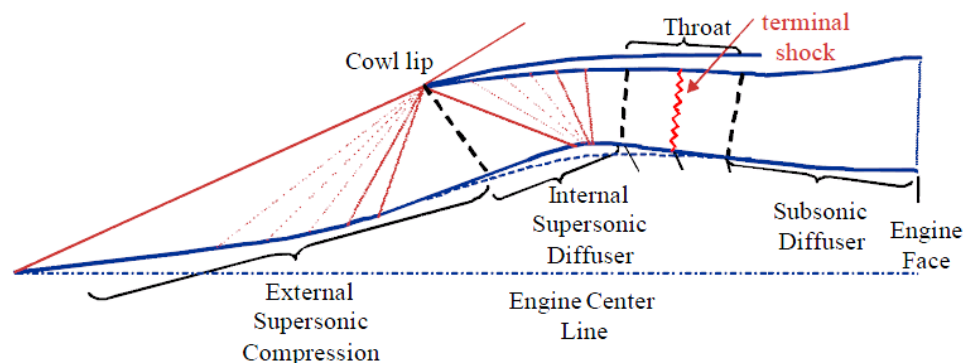


Figure 1.2 Supersonic Air Intake [2]

To make a component test, boundary conditions of the component have to be simulated. In a combustion chamber test, air intake exit conditions (combustion chamber inlet or station 2) have to be simulated. A test at a Mach number of 3 and sea level flight conditions corresponds to a total pressure of 20 bar and a total temperature of 600 K. Mass flow rate of the air depends on the design of the ramjet engine. As a result, a test facility known as direct connected pipe test is needed to supply air at high total pressure

and temperature to the combustion chamber of the ramjet. A schematic view of a direct connected test facility is given in Figure 1.3.

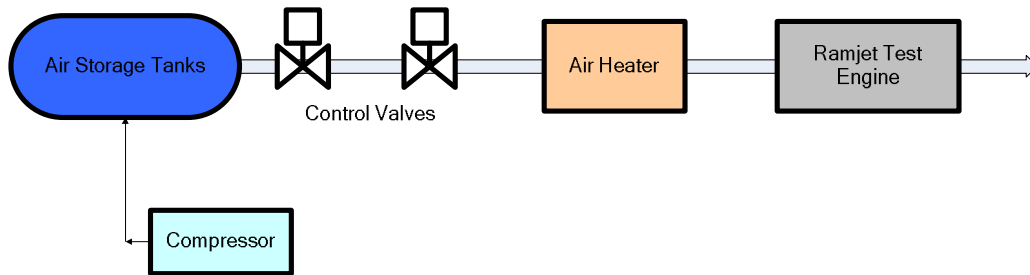


Figure 1.3 Direct Connected Pipe Ramjet Test Facility

To conduct an air inlet test or a coupled air inlet and combustion chamber test, semi free jet or quasi free tests are used. Quasi free, free and semi free tests are based on the same theory, to supply free stream air conditions of the ramjet. Putting the whole missile or aircraft in a supersonic wind tunnel defines the free jet test. This type of test is very expensive and mostly a flight test is preferred at this point rather than a free jet test. The idea behind the semi free jet and the quasi free jet test is to minimize the cross sectional area of the air jet and reduce the required air mass flow rate. Schematic views are given in Figure 1.4. Since all the air is used for combustion chamber at the direct connected test, mass flow rate requirement is minimum. Generally at semi free jet tests, air mass flow rate requirement is at least twice than that of a direct connected test. At a quasi-free jet test, mass flow rate requirement is much higher than that of a semi free jet test.

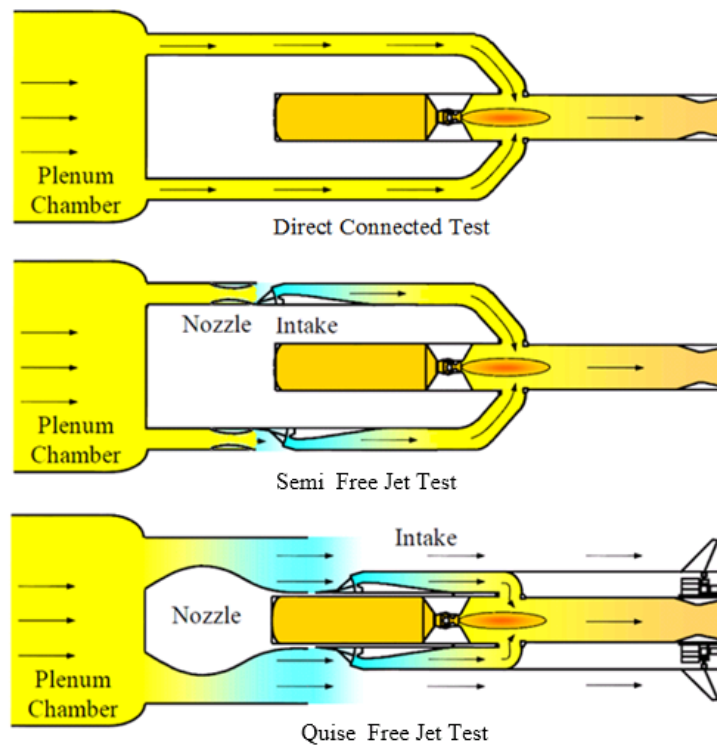


Figure 1.4 Comparison of Direct Connected/Semi Free Jet and Quasi Free Jet Tests

The required pressure and temperature can be supplied with a blow down or continuous type. Power requirements for continuous air flow are prohibitive; therefore, mostly test facilities are of the stored air blow down type. Figure 1.3 is an example of blow down type direct connected pipe test facility. A compressor is used to fill the air tanks. After this operation, by using control valves, pressure is reduced to test pressure and air heater raises the temperature to test temperature. At the end of the air heater, needed pressure and temperature can be supplied. During these sequences, a control system is responsible to supply constant temperature and constant pressure (or to supply a temperature and pressure profile depending on time) to the ramjet combustor. Control valves and air heater are controlled during the run time to supply the required pressure and temperature.

A generic blowdown test facility is formed from 4 main sub-systems:

- Air storage system
- Air heater system
- Control system

Test facility interface and exhaust system

1.1.1 Air Storage System

Air storage system consists of high pressurized air tanks, control valves and a compressor. The capacity of the air tanks specifies the duration of the test. The capacity of the tanks depends on the tank volume and operational pressure limits. The decay of the mass in the air tank decreases the pressure and temperature. This reduction may bring down the temperature to orders of -100°C depending on the pressure reduction. To prevent the icing in the lines, piping and to protect the equipment such as control valves, the tanks should be filled with dry air by using a drier with the compressor.

Control valves have a critical role on the pressure control. Control valves regulate their openings to supply required mass flow rate or pressure. Generally 3 type of valves are used; equal percentage, quick opening and linear. This classification defines the valve capacity profile according to the opening fraction of the valve. The capacity of the valve is explained with flow coefficient, C_v , the number of U.S. gallons per minute of 60°F water (or cubic meters of air at standard pressure and temperature) that will flow through a valve with a one pound per square inch pressure drop. Opening fractions are given in Figure 1.5.

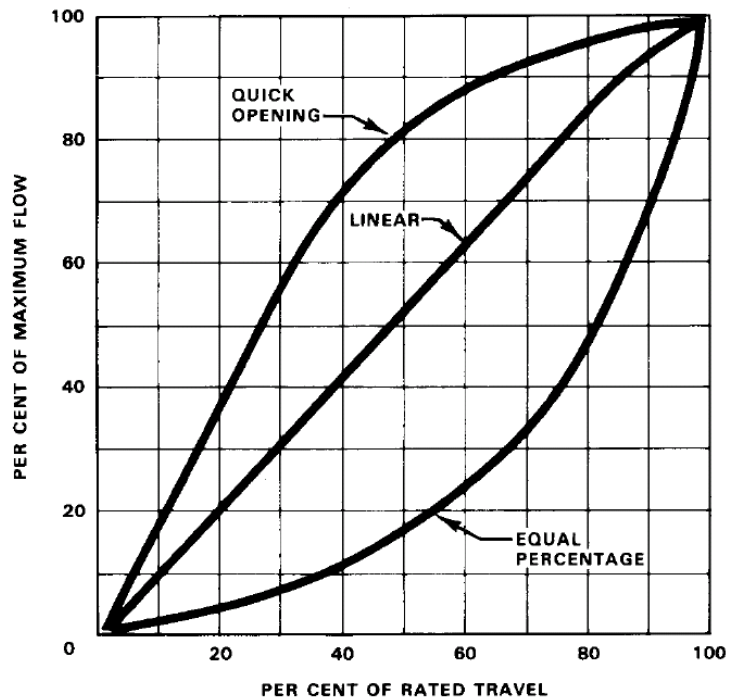


Figure 1.5 Opening Characteristics of Control Valves[3]

Mathematical relations of the open fractions are described;

Linear: $C_v = \text{Valve Opening}$

Quick Opening: $C_v = \text{Valve Opening}^{0.5}$

Equal Percentage: $C_v = \text{Valve Opening}^3$

In linear valves, the flow is directly proportional to the valve opening. A quick opening control valve provides initially larger flows at lower valve openings. But as the valve opens further, the flow decreases to a smaller rate. Equal percentage valve characteristic has opposite behavior and the flow increases rapidly as the valve opens to its full position.

1.1.2 Air Heater System

An air heater system is responsible to raise the temperature of the air which is supplied from the air storage system, to the required temperature. Mainly there are 3 different ways to provide the temperature rise; combustion heaters (vitiator), electric heaters and pebble bed heaters. In some cases, the combination of these systems may be preferred.

Vitiator is a combustion chamber. Hydrogen, kerosene, propane or methane can be used as the fuel in the vitiator. Vitiator of 8 ft high temperature tunnel is given in Figure 1.6. By controlling the fuel mass flow rate, the temperature can be controlled easily. This is the main advantage of the vitiator. But, combustion changes the air contaminant with the combustion products. To minimize this effect and to simulate the real flight condition (air contaminant), additional oxygen (replenishment oxygen) has to be given. Replenishment oxygen keeps oxygen mole fraction constant for the real flight condition. In this view, since the combustion product is only water vapor, hydrogen is more advantageous than hydrocarbon fuels. Nevertheless, hydrocarbon fuels may be preferred because of its handling advantages rather than hydrogen.

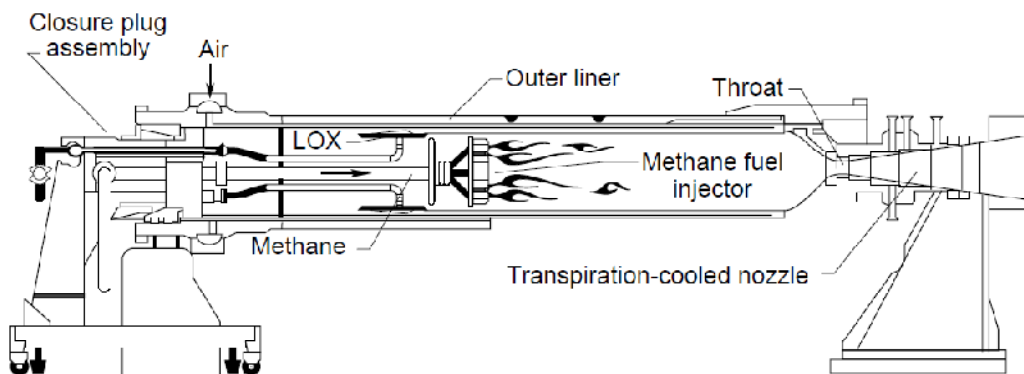


Figure 1.6 Schematic View of Vitiator of 8 ft High Temperature Tunnel [4]

Electric heaters are very useful by not polluting the air and they are easy to control. Their upper temperature limit is higher than that of vitiators. Because of the high temperature, undesired molecules may form such as NOX. Power requirements are in orders of megawatts. To supply this power with an electric heater may not be very

feasible. Generally for high air mass flow rates, an electric heater is not chosen. At NASA Arc Jet Complex, an arc heater is used. At the largest power the supply, it can deliver 75 MW for 30 minutes duration or 150 MW for 15 seconds duration. A photograph is given in Figure 1.7 from the arc jet test [5].

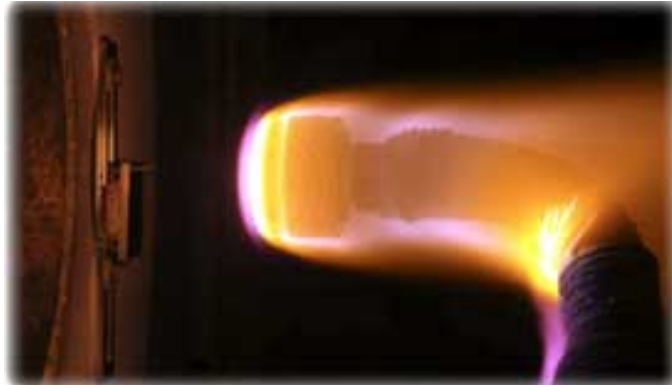


Figure 1.7 NASA Arc Jet Complex [5]

Pebble bed heater systems are beneficial at relatively low temperatures and short test duration requirements. A pebble bed heater contains heat capacitive elements such as ceramic or metal pebbles. These pebbles are heated before the test. During the test, air flow passes through the pebbles and stored energy is used to heat the air. With this concept, temperature control is not possible. Additionally, during the test since the temperature of the pebbles decrease, the exit temperature of the heater decreases, in other words, constant temperature supply is not very easy to maintain for long test durations. A vitiator or an electric heater can be used to heat the pebbles. ONERA S4MA Wind Tunnel is an example of pebble bed heater usage [6]. ONERA S4MA Wind Tunnel will be mentioned under the “Test Facilities” heading.

1.1.3 Control System

Control System consists of the data acquisition system, the control computer which covers the control loops and algorithm. The control algorithm will be mentioned under the “Conceptual Design of a Direct Connected Test Facility” heading.

1.1.4 Test Stand Interface and Ejector System

Ejector system is used to create high altitude low pressure conditions at the end of the engine. Ejector system is important to observe nozzle performance. As the test is not focused on the nozzle performance and since the thrust data can be manipulated and corrected, ejector system is not an essential subsystem. For small mass flow rates and short test duration, a vacuum chamber can be sufficient, but for higher mass flow rates an ejector system with a stream generator is used. Figure 1.8 is a generic ejector system with a steam generator.

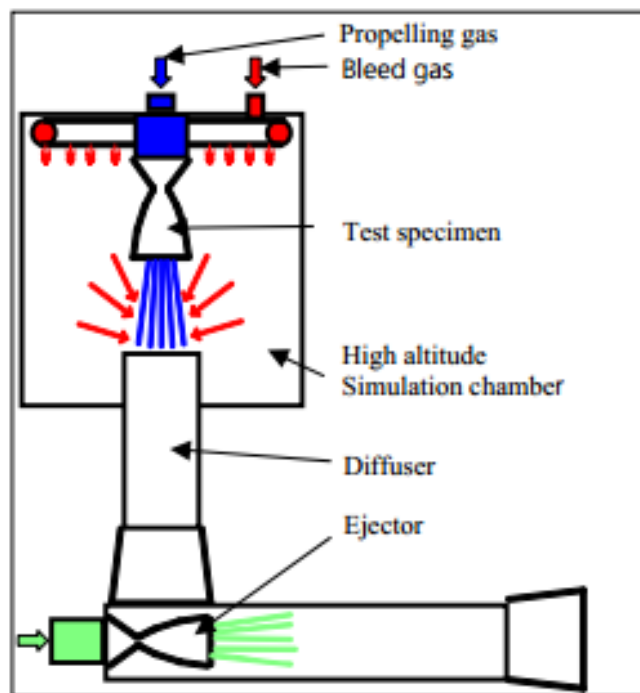


Figure 1.8 Ejector System[7]

The interface between ramjet engine and test facility has to have freedom at thrust vector. Since the thrust vector control is not under this scope, one degree of freedom will be sufficient. Flexible metal piping and slider V-blocks are used to maintain one degree of freedom. Flexible joints and slider V-blocks can be seen in Figure 1.9.

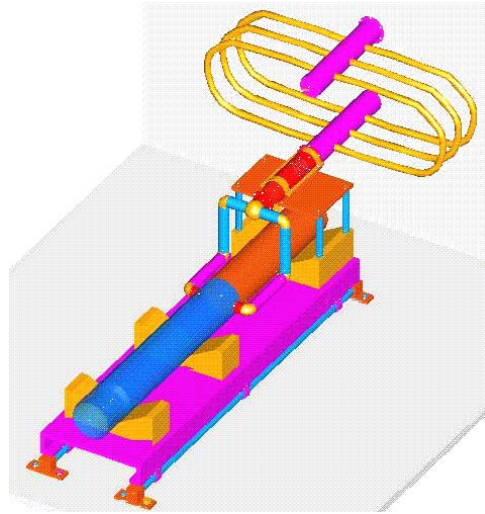


Figure 1.9 Engine and Test Facility Interface [8]

The design of the interface is very important for the dynamics of the system. Pressure loss in the flexible piping and volume of the manifolds may cause the facility to become unstable. Additionally, the heat capacity of the interface has a great influence on the test facility dynamics. In Figure 1.10, flexible joints are placed upstream of the heater. Thereby, heat loss can be minimized. In this way, the heater has freedom at thrust vector.

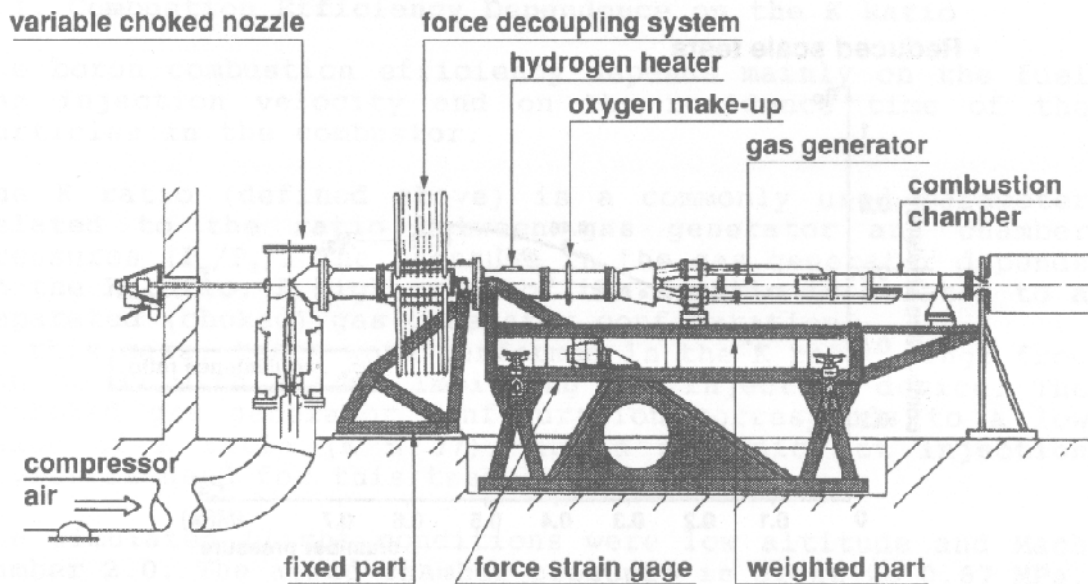


Figure 1.10 Sketch of Ramjet Engine and Direct Connected Test Facility [9]

1.2 LITERATURE SURVEY

1.2.1 Test Facilities

1.2.1.1 Direct-Connect Supersonic Combustion Test Facility (DCSCTF)

The NASA Langley Direct-Connect Supersonic Combustion Test Facility (DCSCTF) has historically been used to test ramjet and scramjet combustor models at stagnation enthalpies duplicating that of flight at Mach numbers between 3.5 and 7.5. Data acquired using the facility is typically used to assess the mixing, ignition, flame-holding and combustion characteristics of ramjet or scramjet combustor models. A hydrogen-air combustion heater is used to produce the required high enthalpy test gas. Oxygen is replenished in the heater to obtain a test gas with the same molar oxygen content as standard air, 0.2095 [10]. Feeding system of the hydrogen air vitiator can store oxygen and hydrogen at a maximum pressure 165 bar and before air vitiator oxygen and hydrogen is regulated to 50 bar [4].

Various fuels may be supplied to the ramjet or scramjet combustor models including gaseous hydrogen, gaseous hydrocarbons, and heated liquid hydrocarbons[10].

Addition of pressure and temperature transmitter, Schlieren/shadowgraph Coherent Anti-stokes Raman Spectroscopy (CARS) are the main instrumentation capabilities of DCSCTF [10].

Two different views of NASA Direct-Connect Supersonic Combustion Test Facility are in Figure 1.11 and Figure 1.12



Figure 1.11 NASA Langley DCSCTF [10]

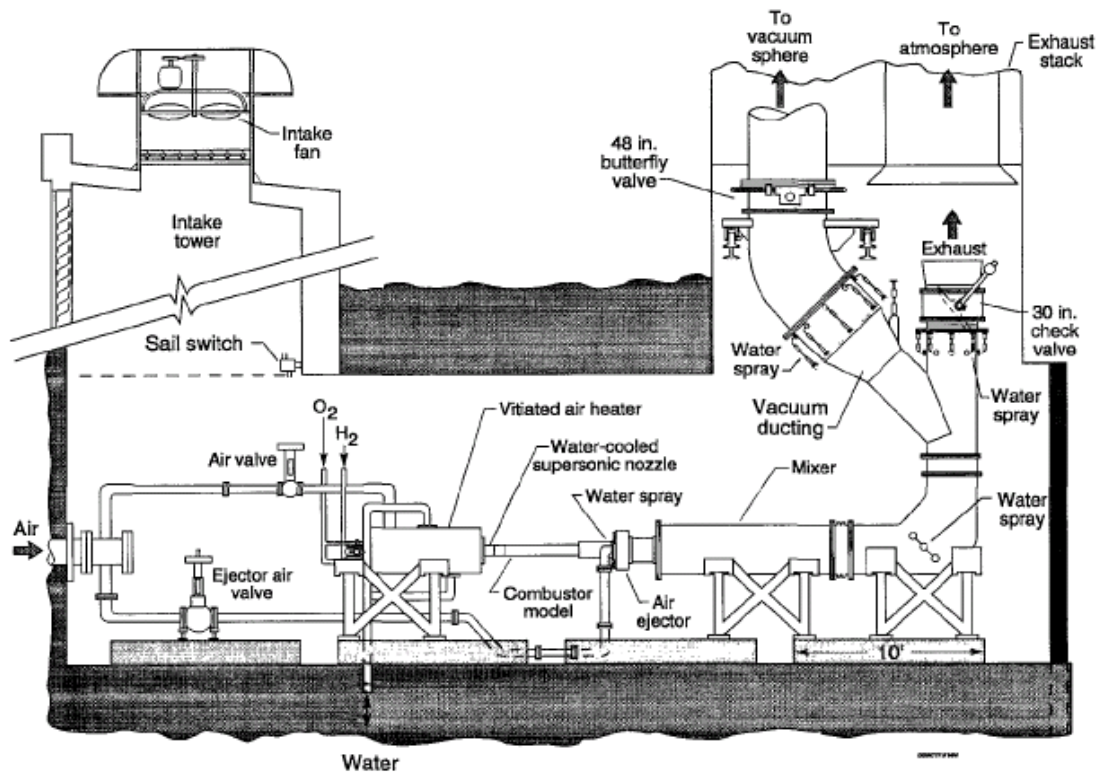


Figure 1.12 Schematic View of DCSCTF[4]

General characteristics are listed in Table 1-1.

Table 1-1 The NASA Langley DCSCTF General characteristics [4]

Air Heater	Hydrogen Vitiatior
Simulated Flight Mach Number	3.5 – 7.5
Stagnation Temperature	720 – 2100 K
Stagnation Pressure	8 – 34 bar
Maximum Run Time	60 s
Runs per day	5 - 20

Mass flow rate of the test gas (hydrogen air combustion products with replenishment oxygen) can be regulated between 0.45 – 13.6 kg/s. Operation map of the DCSCTF is given in Figure 1.13. The left boundary is the lower temperature limit of stable operation of the heater (720 K) and the right boundary represents the maximum operational stagnation temperature (2100K). The lower (diagonal) boundary reflects the maximum allowable heater pressure (34 bar) and the upper boundary reflects the lowest pressure for stable heater operation (8 bar);

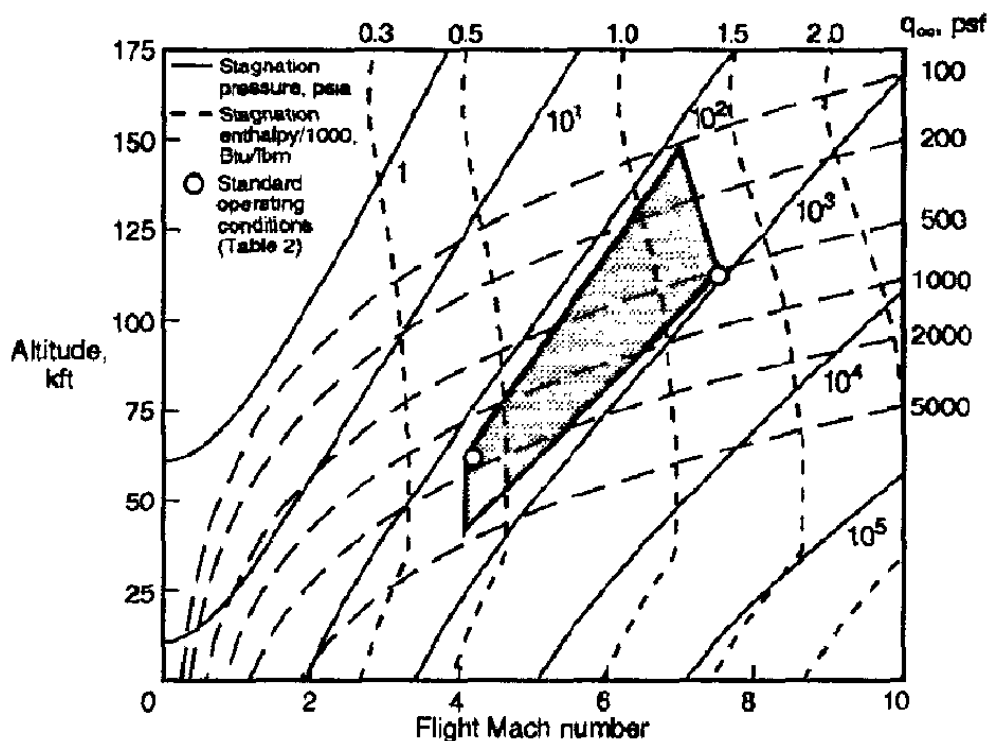


Figure 1.13 DCSCTF Operation Map[4]

1.2.1.2 Combustion Heated Scramjet Test Facility (CHSTF)

The NASA Langley Combustion Heated Scramjet Test Facility (CHSTF) is very similar to DCSCTF [10]. CHSTF has historically been used to test complete (inlet, combustor and partial nozzle) subscale scramjet component integration models. The facility uses a hydrogen and air heater capable of producing stagnation enthalpies duplicating that of flight at Mach numbers ranging from 3.5 to 6. Oxygen is replenished in the heater to

obtain a test gas with the oxygen mole fraction of air (0.2095). The test gases are hydrogen air combustion products with oxygen replenishment. Air for the CHSTF is supplied from a high pressure bottle field and is regulated to 38 psia (nominal) before to entering into the test cell. Oxygen and hydrogen is stored at 165 bar similar to DCSCF. Purge nitrogen is also supplied from a tube trailer at a maximum pressure of 165 bar with the pressure regulated to 16 bar. Ignition of the gas mixture is achieved using an electric-spark-activated hydrogen/oxygen torch igniter. The vacuum for altitude simulation is provided by a 1.8 m diameter vacuum sphere/steam ejector system (requiring up to 11300 kg/hr of steam). Test gas mass flow rates range from 6.8 to 27 kg/s.

Just like DCSCF, this facility is capable of supply the gaseous hydrogen (at ambient temperature) used as the primary fuel in the scramjet engines. Six-component force balance system, pressure transducers, temperature transducers, heat transfer transducers and Schlieren system are available to get data from an engine.

General characteristics are listed in Table 1-2. Views of NASA Combustion Heated Scramjet Test Facility is shown in Figure 1.14 and Figure 1.15.

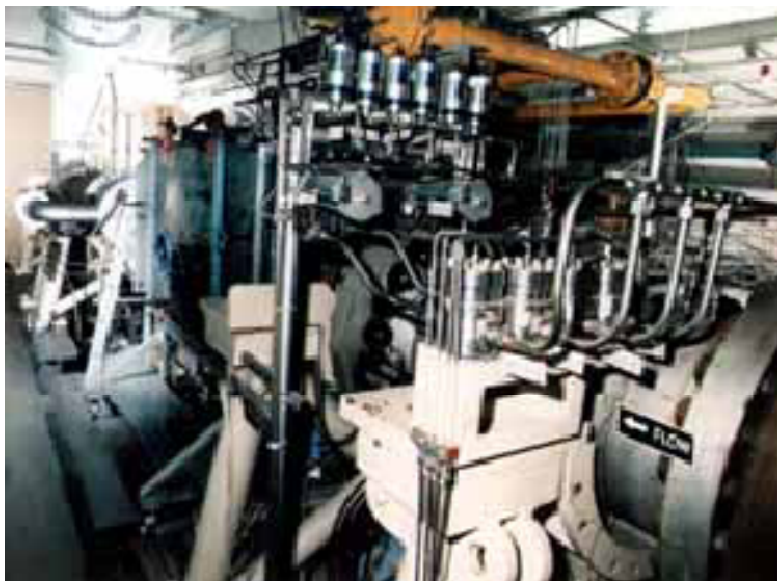


Figure 1.14 NASA Langley CHSTF [10]

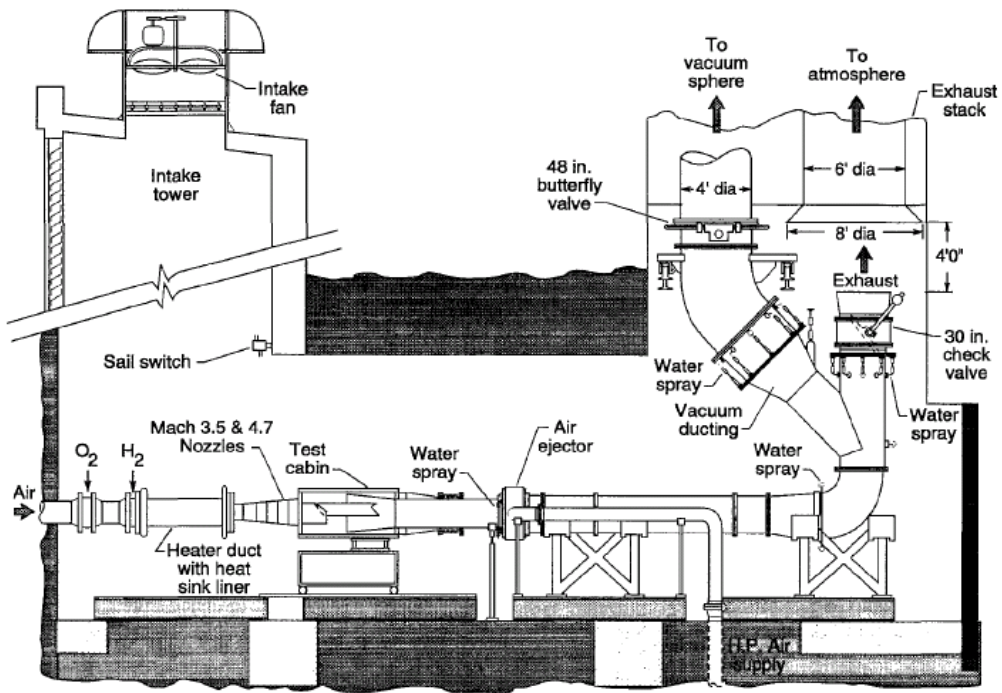


Figure 1.15 Schematic view of CHSTF [4]

Table 1-2 General Characteristics of The NASA Langley CHSTF[4]

Air Heater	Hydrogen Vitiator
Simulated Flight Mach Number	3.5 - 6
Stagnation Temperature	720 – 1650 K
Stagnation Pressure	3.4 – 34 bar
Maximum Run Time	30 s
Runs per day	5 - 10

1.2.1.3 Arc-Heated Scramjet Test Facility (AHSTF)

The purpose of the Arc-Heated Scramjet Test Facility (AHSTF) is to test complete, subscale, scramjet component integration models in flows with stagnation enthalpies duplicating that of flight at Mach numbers from 4.7 to 8 [4]. Schematic view of the AHSTF is given in Figure 1.16. The flow at the exit of the nozzle simulates the flow entering a scramjet engine module in flight. The stagnation enthalpy necessary to simulate flight Mach number for the engine tests is achieved by passing air through a rotating electric arc. The arc heater is powered with two 10 megawatt direct-current power supplies [10]. This heating process results in a test gas containing small amounts of nitric oxide.

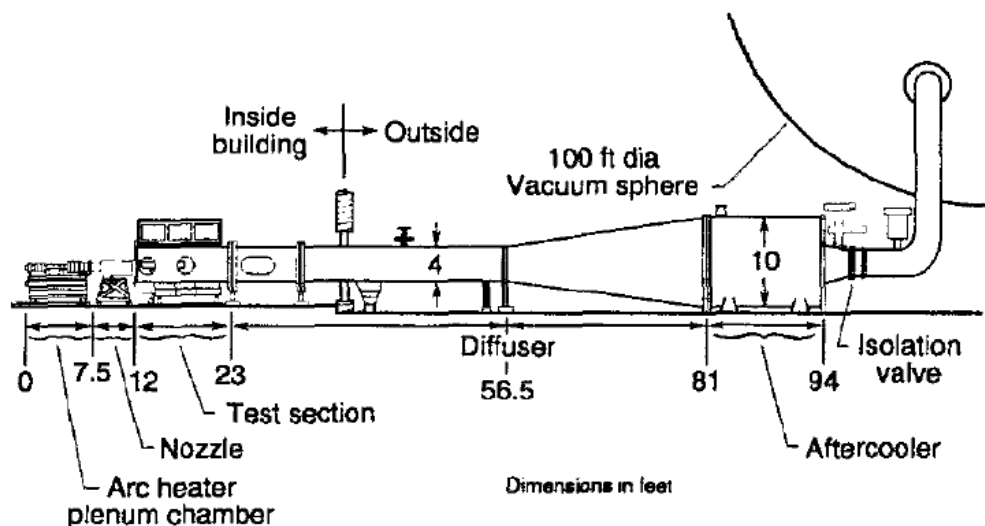


Figure 1.16 Schematic View of Arc-Heated Scramjet Test Facility [4]

Mass flow rate of the air can be controlled between 0.2 to 1 kg/s according to the test condition [10]. This facility is capable of supplying gaseous hydrogen (at ambient temperature) used as the primary fuel in the scramjet engines. Six-component force balance system, pressure transducers, temperature transducers, heat transfer transducers and Schlieren system are available for obtaining data from an engine.

General characteristics are listed in Table 1-3. A view of NASA Langley Arc-Heated Scramjet Test Facility is presented in Figure 1.17.

Table 1-3 NASA Langley AHSTF General Characteristics [10]

Air Heater	Electric Arc Heater
Simulated Flight Mach Number	4.7 - 8
Stagnation Temperature	1100 – 2900 K
Maximum Stagnation Pressure	45 bar
Maximum Run Time	30 s (Mach=8) 60 s (Mach=6)
Runs per day	4-6

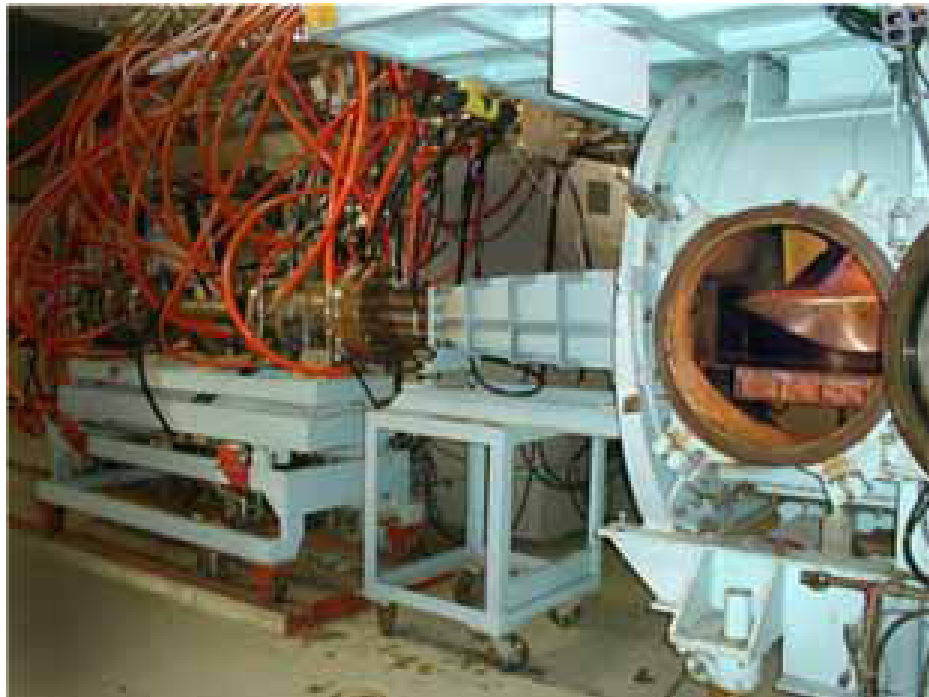


Figure 1.17 NASA Langley AHSTF [10]

1.2.1.4 8-Foot High Temperature Tunnel

The Langley 8-Foot High Temperature Tunnel (8-ft. HTT) duplicates true total enthalpy at hypersonic flight conditions for testing advanced large-scale, flight-weight aerothermal, structural and propulsion concepts. The 8-ft. HTT is a methane/air combustion-heated hypersonic blow-down facility with vacuum for altitude simulation provided by an air ejector. Oxygen is replenished in the test gas for air-breathing propulsion tests to achieve the standard atmospheric mole fraction of oxygen. The facility provides simulation of flight conditions at Mach numbers of 4, 5, and 7 through a range of altitudes from 14,000 to 36,000 feet. The 26-foot diameter test section, which contains the 8-foot diameter by 12-foot long flow test flow space, will accommodate very large models, air-breathing hypersonic propulsion systems, and structural and thermal protection system components. Additional simulation capabilities are provided by a radiant heater system that can be used to simulate ascent or entry heating profiles. Typical test duration is approximately 60 seconds[10].

General characteristics are listed in Table 1-4. Although the maximum stagnation pressure is 240 bar, oxygen replenishment reduces the pressure limit to 140 bar.

Table 1-4 NASA Langley 8-Foot High Temperature Tunnel General Characteristics [10]

Air Heater	Methane vitiator
Simulated Flight Mach Number	4 - 7
Stagnation Temperature	900 – 2000 K
Maximum Stagnation Pressure	240 bar
Maximum Run Time	60 s

1.2.1.5 Air Force Research Laboratory Direct Connect High-Enthalpy Supersonic Combustion Test Facility

This facility is a continuous flow high enthalpy direct connected test facility. 3.5 - 7 Mach flight conditions can be simulated. In this facility 2500 K stagnation temperature is sustained by a vitiator. The fuel of the vitiator can be a liquid fuel such as JP-4 or gaseous fuels. Main components are water cooled; vitiator, instrumentation and nozzles are also included[11]

Table 1-1 Air Force Research Laboratory Direct Connect High-Enthalpy Supersonic Combustion General Characteristics [10]

Air Heater	Vitator
Simulated Flight Mach Number	3.5 - 7
Maximum Stagnation Temperature	2500 K
Maximum Stagnation Pressure	240 bar
Maximum Run Time	Continuous

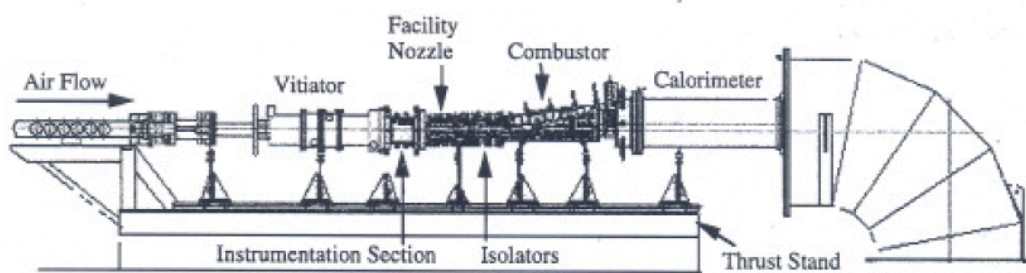


Figure 1.1 Direct Connect High-Enthalpy Supersonic Test Facility [11]

1.2.1.6 AEROJET Ramjet Test Facility

Propane air vitiator is used at AEROJET test facility. The schematic view of the test facility is shown in Figure 1.2. This facility is used at the development of the MARC-R282 ramjet engine. Installed engine in the facility is shown on Figure 1.3. Oxygen added air (21% mole fraction) is given to the ramjet engine. At the exit of the engine, not a convergent divergent but a convergent nozzle is used to measure the thrust data and to calculate efficiency data more accurately. During the MARC-R282 engine tests, the facility supplied 38 kg/s test air (air/propane combustion reactants and replenishment oxygen) at 660 K and 8.6 bar [12].

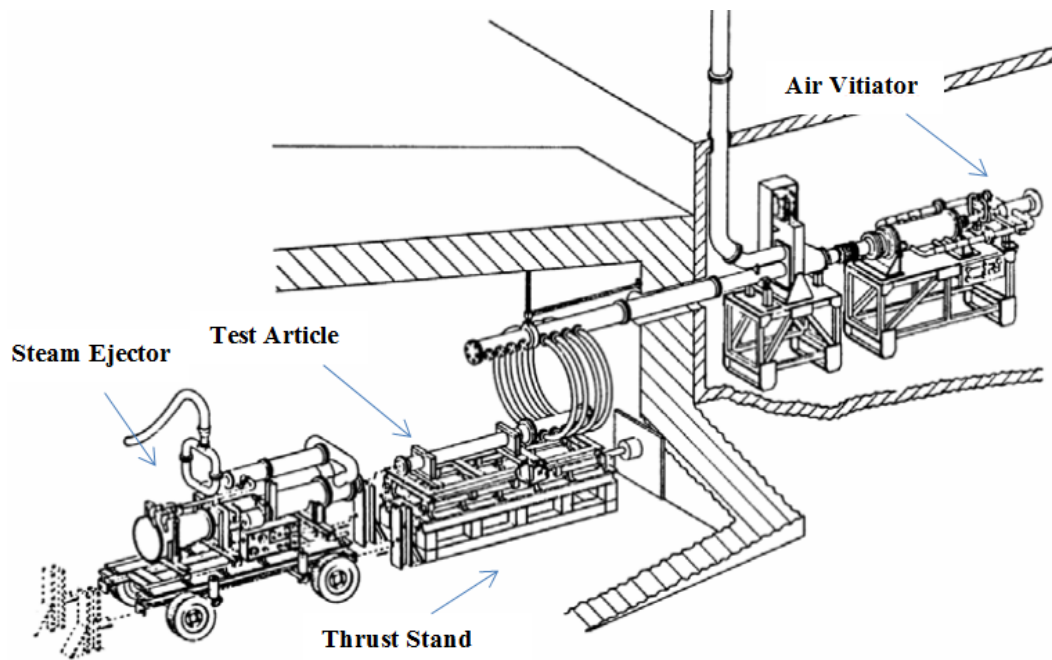


Figure 1.2 AEROJET Ramjet Test Facility[12]

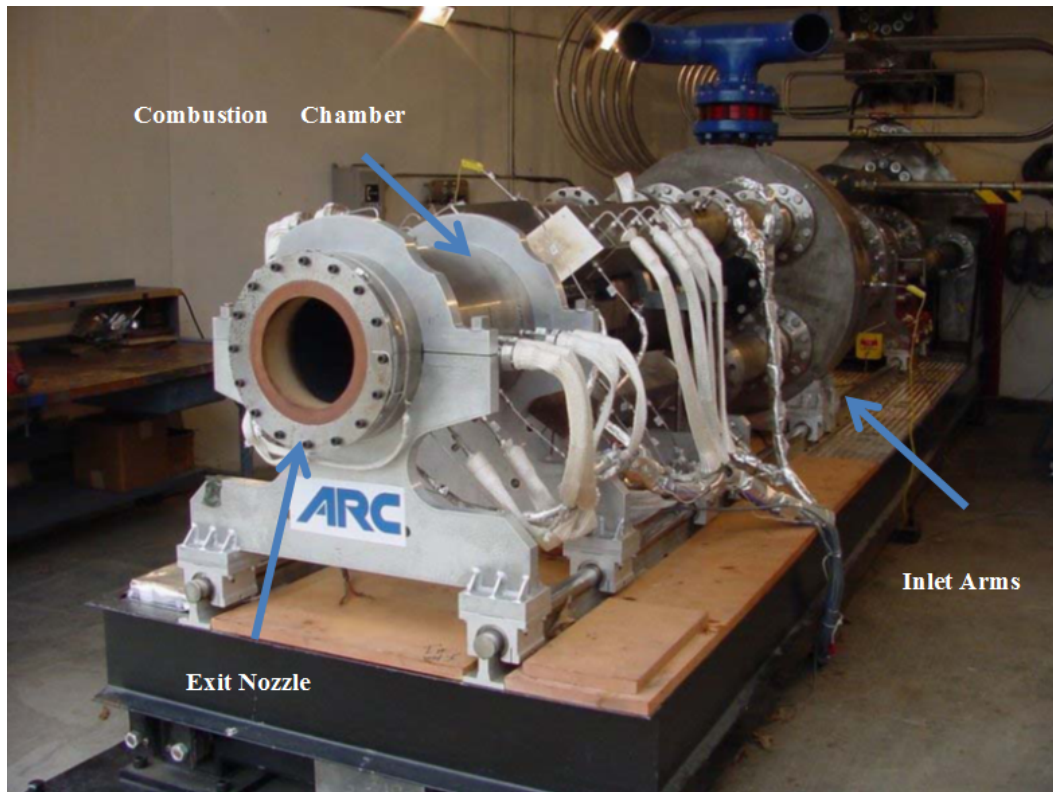


Figure 1.3 MARC-R282 Ramjet Engine at Direct Connected Test Facility[12]

The interface of the test facility and the ramjet engine is shown in Figure 1.4. Before the combustion chamber of the ramjet engine, sonic Venturies are used to isolate the upstream flow oscillations. This sonic Venturi is also used as flowmeter, for the calculation of stagnation temperature, stagnation pressure and flow area.

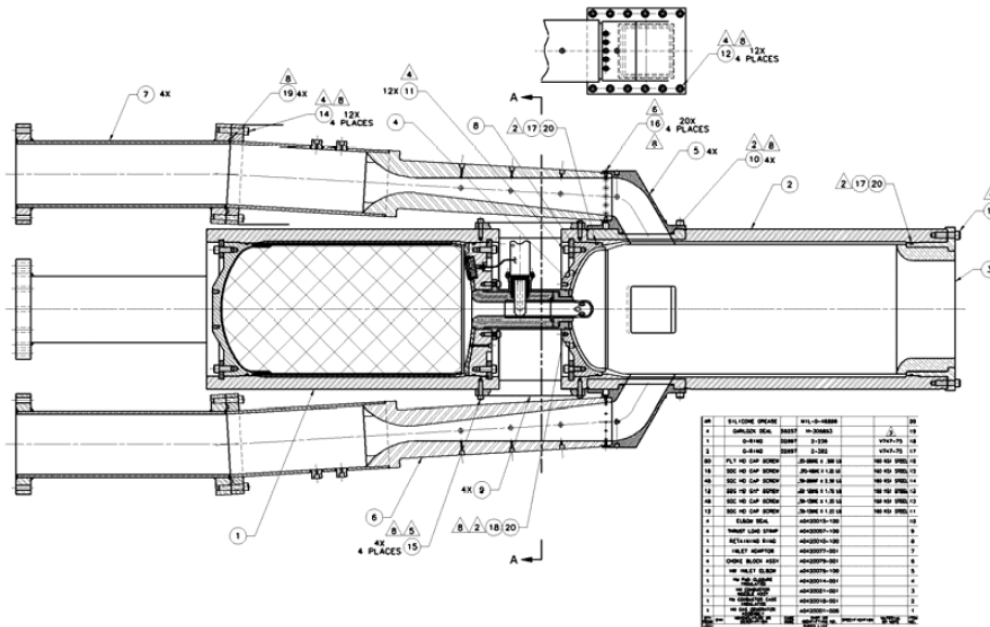


Figure 1.4 Ramjet Engine and Direct Connected Test Facility Interface[12]

1.2.1.7 Bayern-Chemie Ramjet Test Facilities

Bayern-Chemie is recently working on METEOR program. During this program direct connected tests and quasi-free jet test are made at Ramjet Test Facilities (Figure 1.5). Figure 1.6 shows the installed engine on the direct connected test and quasi free jet test bench. 150 kg/s of mass flow rate is applicable. Stagnation temperature is supplied by a hydrogen vitiator. The value of the air supply system is 75 m³ and it is at a pressure of 300 bar. Vitiator fuel hydrogen and replenishment oxygen are stored in gas bottles. Nitrogen gas is used in the vitiator feeding system to purge the piping and stored like hydrogen and oxygen [13].

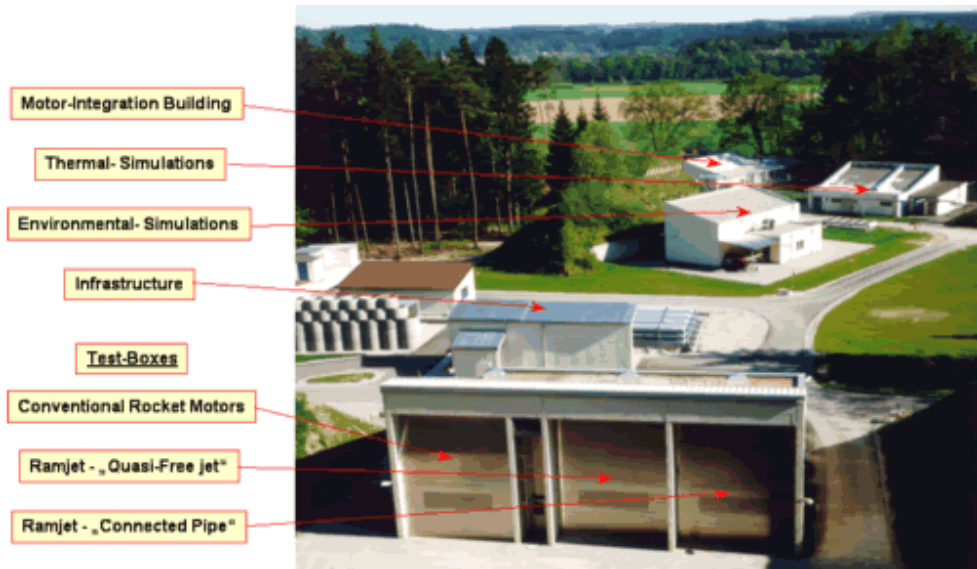


Figure 1.5 Bayern-Chemie Ramjet Test Facilities [14]

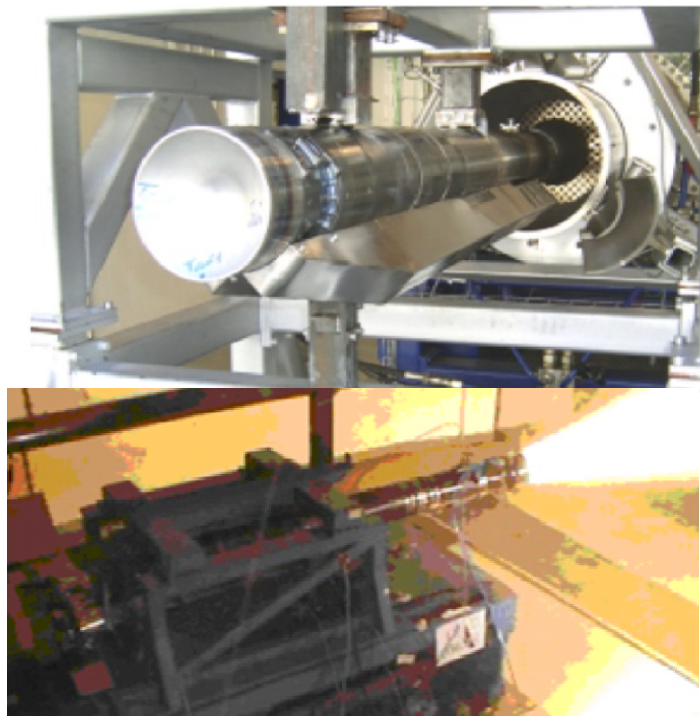


Figure 1.6 Meteor Program Quasi free Jet and Direct Connected Tests[13]

1.2.1.8 ONERA ATD 5

This test facility is used to perform direct connected pipe tests. Mach number up to 7.5 Mach can be simulated which refers to 2400 K. Air is heated by a hydrogen vitiator and replenishment oxygen is added to the test air. Air temperature is raised to 2400 K by using a pre-heater. The pre-heater raises the temperature to 1000K. Maximum mass flow rate and pressure of air is 4 kg/s and 40 bar respectively[6].

1.2.1.9 ONERA S4MA Windtunnel

S4MA windtunnel is capable to simulate 6.4 Mach or 10 Mach. Maximum stagnation temperature and pressure of the windtunnel are 150 bar and 1850 K respectively [15]. A pebble bed heater, 10 tons of alumina, are used to heat the air. Schematic view of S4MA windtunnel is given in Figure 1.7. Vacuum sphere volume is 4000 m³ and the pressure range is 20 to 80 mbar. Vacuum pressure can be supplied according to the test condition. Maximum mass flow rate of the windtunnel is 30 kg/s [15].

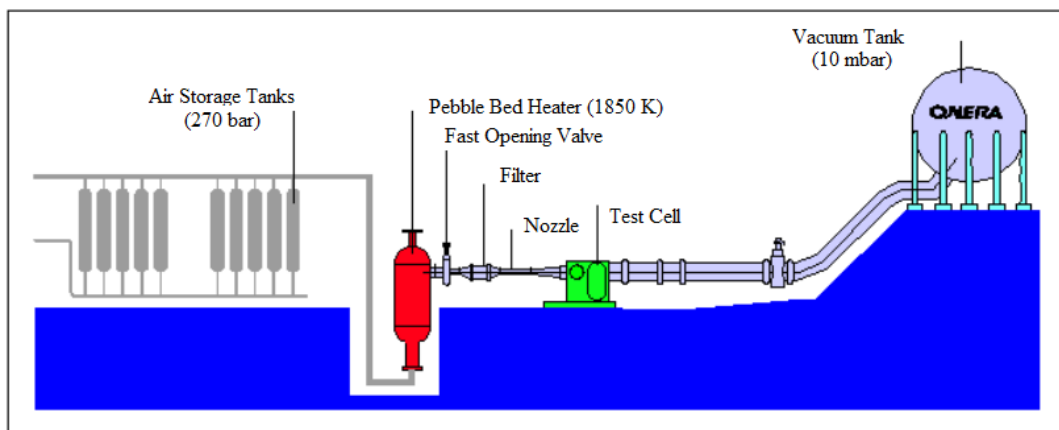


Figure 1.7 ONERA S4MA Windtunnel Schematic View [15]

The pebble bed is heated by combustion of propane/air before the test. Test duration depends on the air storage capacity and heat storage capacity of the pebble bed heater. Depending on the test condition, test duration can be at least 25 seconds. Propane storage system is shown in Figure 1.8.



Figure 1.8 Propane Storage and Feeding System [15]

CHAPTER 2

CONCEPTUAL DESIGN OF A DIRECT CONNECTED RAMJET TEST FACILITY

2.1 REQUIREMENT ANALYSIS

Test facility which is designed in this study, is used for ramjet engine combustor test. Thus requirement analysis is based on a ramjet engine. In this chapter an operating condition is defined and this condition is used to configure the test facility.

Control volume of a ramjet engine is shown in Figure 2.1.

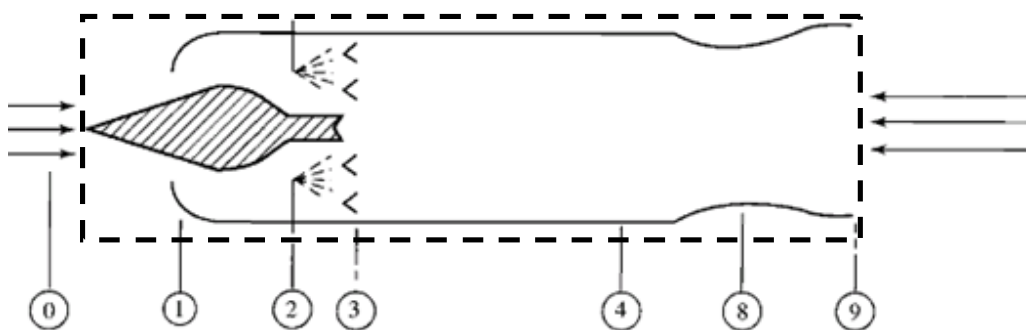


Figure 2.1 Control Volume of a Ramjet

Uninstalled thrust of Ramjet engine is defined as;

$$F_N = \dot{m}_1 V_1 - \dot{m}_9 V_9 + A_9(p_9 - p_1) \quad (2.1)$$

F_N : Uninstalled thrust

\dot{m}_1/\dot{m}_2 : Mass flow rate of referred station

V_1/V_2 : Velocity value of referred station

A: Area

Thrust is maximized when flow through the nozzle is expanded to the flight ambient pressure. That is when $p_9 = p_1$. In this case optimum thrust becomes.

$$F_N = \dot{m}_1 V_1 - \dot{m}_9 V_9 \quad (2.2)$$

Additionally, if the mass flow rate of the fuel can be ignored, the assumption of $\dot{m} = \dot{m}_1 = \dot{m}_9$ can be done for simplifications.

$$F_N/\dot{m} = V_1 - V_9 \quad (2.3)$$

If velocity values are defined as a function of speed of sound;

$$V_1 = M_1 a_1 = f(M_1, \gamma_1, R_1, T_1) \quad (2.4)$$

$$V_9 = M_9 a_9 = f(M_9, \gamma_9, R_9, T_9) \quad (2.5)$$

Other assumptions and relations;

$$R_9 = R_1 = R \quad \gamma_9 = \gamma_1 = \gamma \quad (2.6)$$

T_1 ; where is the temperature of the atmosphere which is a function of altitude.

p_1 ; where is the pressure of the atmosphere which is a function of altitude.

Only unknown terms are T_9 and M_9 . M_9 is calculated by using the ideal expansion on nozzle. Thus firstly total pressure at the nozzle exit have to be known. p_{t9} is defined as

$$p_{t9} = p_{t1} \left(\frac{p_{t2}}{p_{t1}} \right) \left(\frac{p_{t4}}{p_{t2}} \right) \left(\frac{p_{t9}}{p_{t4}} \right) \quad (2.7)$$

First term, p_{t1} , is calculated by using p_1 and M_1 in equation below;

$$p_{t1} = f(M_1, p_1) = p_1(1 + 0.5 \times (\gamma - 1)M_1^2)^{\gamma/(\gamma-1)} \quad (2.8)$$

$\frac{p_{t2}}{p_{t1}}$ term is defined in previous section as pressure recovery factor. This value is calculated from reference [16] as a function of flight Mach number (M_1). Relation is given bellow

$$p_{rc} = \begin{cases} 1 - 0.0776(M_1 - 1)^{1.35}, & 1 < M_1 < 5 \\ 800/(M_1^4 + 935), & M_1 > 5 \end{cases} \quad (2.9)$$

$\frac{p_{t4}}{p_{t2}}$ term is defined as pressure loss at combustion chamber and this value is taken 1.

Similarly $\frac{p_{t9}}{p_{t4}}$ term is defined as nozzle efficiency and taken as 1.

After all these assumptions; p_{t9} is defined as a function of pressure recovery factor and p_{t1} which is given in as;

$$p_{t9} = p_{t1}p_{rc} \quad (2.10)$$

There by M_9 is calculated.

$$M_9 = \frac{2}{\gamma_9 - 1} \left[\left(\frac{p_{t9}}{p_9} \right)^{(\gamma-1/\gamma)} - 1 \right] \quad (2.11)$$

Last unknown T_9 is calculated by using isentropic relation which is shown in equation below;

$$T_9 = f(\text{Mach}_9, Tt_9) = Tt_9 / (1 + 0.5(\gamma - 1)M_9^2) \quad (2.12)$$

Far an adiabatic and ideal nozzle Tt_9 is equal to Tt_4 . Thus thrust over air mass flow, F/\dot{m} , term is defined as a function of flight Mach number, altitude and Tt_4

$$F/\dot{m} = f(M_0, \text{Altitude}, Tt_4) \quad (2.13)$$

Altitude is selected “0” at the sea level and these equations are set to be solved for different values of M_0 Mach numbers and Tt_4 temperature. The results are shown in Figure 2.2. Mach 2 is selected since it is the optimum Mach number for an ideal ramjet.

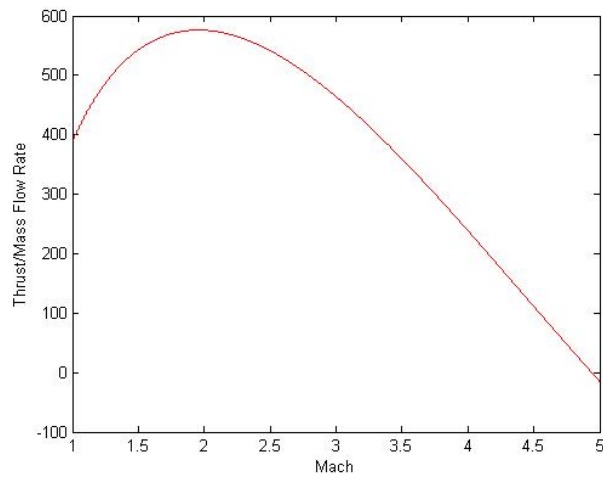


Figure 2.2 Thrust Variation

Other system requirements test duration and air flow rates are defined as 2 minutes and 10kg/s respectively. Flight envelope of the ramjet engine is given in Figure 2.3.

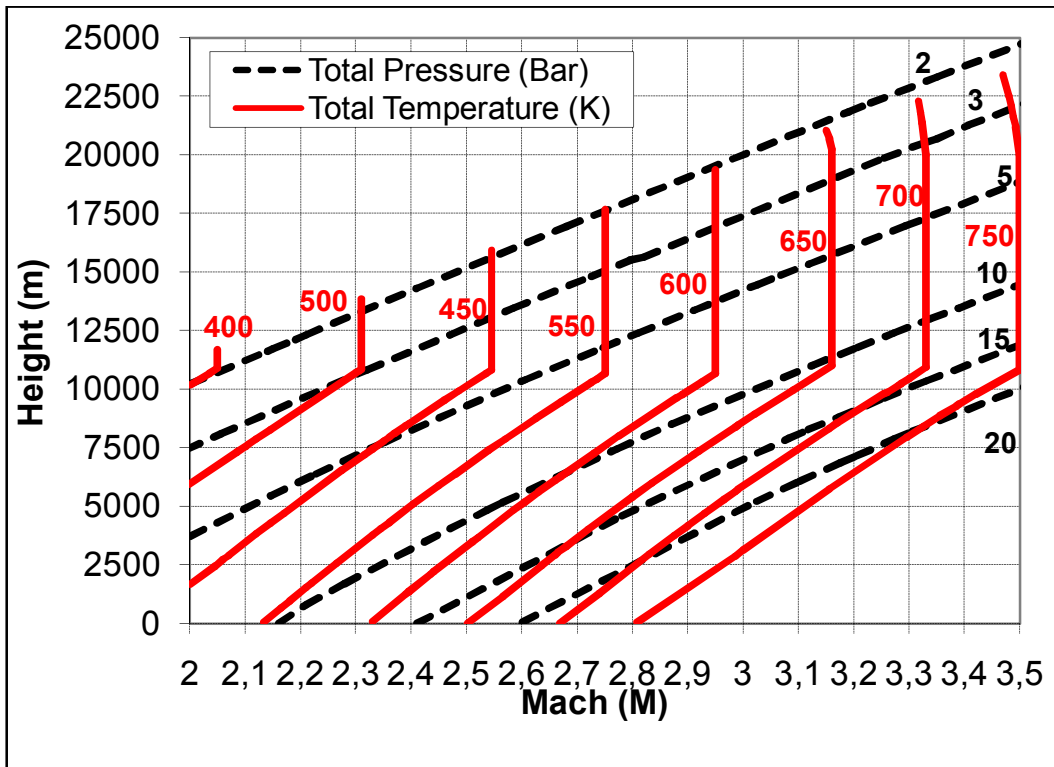


Figure 2.3 Ramjet Flight Envelope and Simulation Requirements

Constant temperature lines are found out by calculating total temperature values using isentropic relations. These temperature values represents Tt_0 , Tt_1 and Tt_2 ($Tt_0 = Tt_1 = Tt_2$). Values of Pt_0 and Pt_1 are calculated by using of the isentropic relations and then the total pressure of the combustion chamber is evaluated by multiplying the pressure recovery factor.

In Figure 2.3; right lower limit represents the structural limit (high pressure). High altitude limits the combustion performance and high Mach number imposes the temperature limit. This graph indicates that, test facility has to be capable of supplying 400K-1000K temperature and 2bar-20bar and pressures.

2.2 CONCEPTUAL DESIGN OF DIRECT CONNECTED TEST FACILITY

2.2.1 Air Storage System

Air tank capacity is related to the test duration. For a 120 second direct connected test, at least 1200 kg air must be supplied at a constant mass flow rate of 10 kg/s. Before the steady state is condition is readed, (supplying required mass flow rate at the required temperature) test set-up consumes air to fill the lines. This consumption has to be taken into account. For this reason 1200 kg of air is multiplied by a safety factor of 1.25 and 1500 kg of air is obtained. Other design parameters of the air storage tank are the; volume, operating (initial) pressure and minimum pressure. Operating pressure refers to initial (maximum) pressure of the tank. It should be noted that during the blow down test, tank pressure decreases. High operating pressure can be useful to select smaller storage tanks. However, high operating pressure means, control valves have to handle high pressure drop. Minimum pressure is defined as tank pressure value when the blow down test ends up. This means that the test is carried out between the operating pressure and minimum pressure. From flight envelope of a ramjet engine, test set-up has to be capable of supplying 20 bars of pressure. Thus at the end of blow down test (120 sec) air storage tank pressure has to be higher than 20 bar. For this reason, the minimum pressure is selected as 50 bar.

To decide the operating pressure, a trade-off study is done by trying different sizes for the tank. Parameters of this trade-off are given in Table 2-1. Volume is selected randomly and the initial pressure is found out to store 1500 kg air between operating pressure and minimum pressure (50 bar). Initial temperature is taken as 288 K.

Table 2-1 Trade-off Parameters for the Size of the Air Storage Tank

Parameter	I	II	III	IV	V
Volume (m ³)	54	36	18	9	6
P _i (bar)	73	85	120	190	260
T _i (K)	288	288	288	288	288

During the blow down test, total pressure and total temperature decreases as the air leaves the tank. For each solution, steel having a thickness of 40 mm is used as the tank material and surface area is calculated according to its volume with 1m diameter. Trade-off problem is summarized schematically in Figure 2.1.

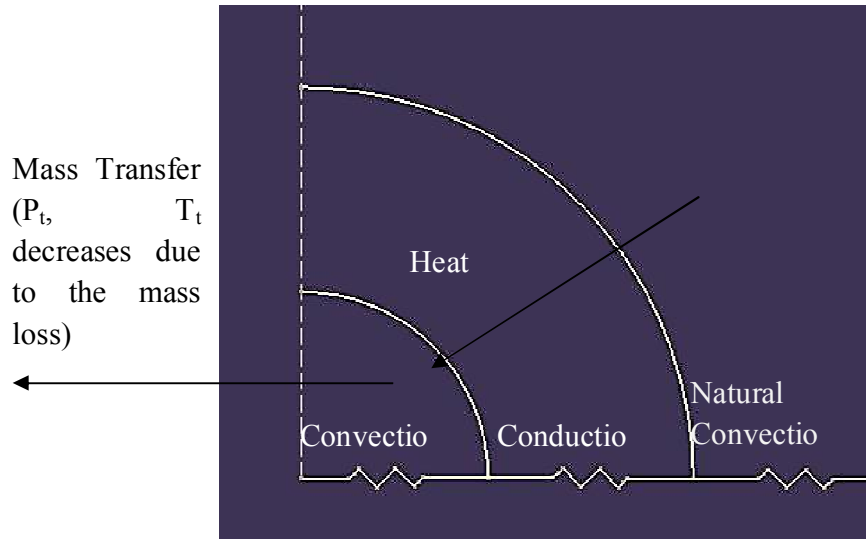


Figure 2.1 Trade-off Problem for Sizing The Air Storage Tank

This transient problem is solved by using 1 dimensional Computational Fluid Dynamic (CFD) code FLOWNEX which is described in chapter 3. Tank pressure drop and tank temperature drop values after 100s is compared in Figure 2.2. This trade-off shows that decrease in tank volume increases the pressure difference and temperature difference dramatically. Pressure and temperature differences are defined as;

$$\Delta p = p_{t=0} - p_{t=100} \quad (2.14)$$

$$\Delta T = T_{t=0} - T_{t=100} \quad (2.15)$$

Subscript t=0 and t=100 indicates the condition of initial condition and when time is equal to 100s respectively.

Minimum pressure is selected as 50 bar. This means that at the end of the test, 50 bar air will be unused. Table 2-1 shows the advantages of high and low volume tank opportunities.

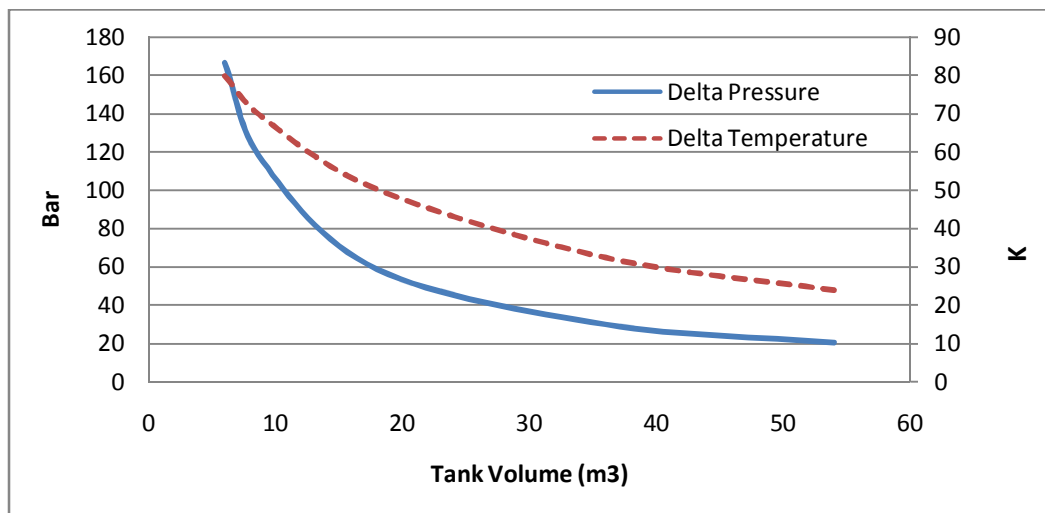


Figure 2.2 Pressure and Temperature Drop After 100 s

Table 2-1 Tank Size Comparison

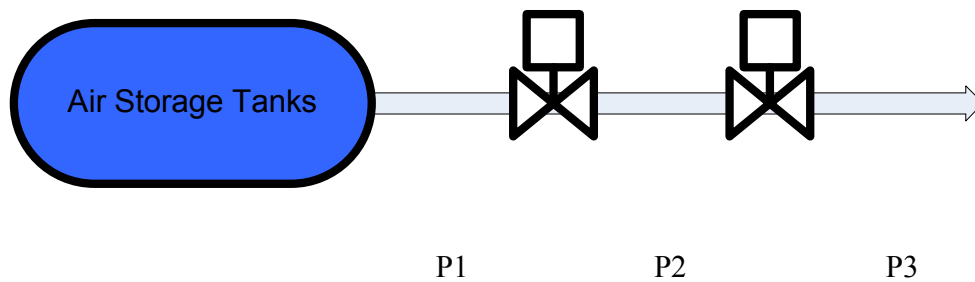
Configuration	Properties
Higher volume tank	pressure drop is low
	temperature drop is low
	more stable, more easy for control valve
	operating pressure is low, tank thickness requirement is less
Lower volume tank	high volumetric loading
	unused air amount is less, filling time is less

After this trade-off study an air storage tank having a volume of 18 m³ and 120 bar configuration is chosen.

The second step is to decide on the control valve. The control valve should be capable of reducing the pressure to a range of 2 to 20 bar when up-stream pressure (tank pressure) is between 120 bar to 50 bar. In this case the pressure ratio is; 120 bar /2 bar. Since the pressure ratio is quite high, to supply mass flow rate in a wide range is not possible by using one control valve. Two control valves are selected to be used on the line simultaneously. Different cases are created to decide the valve sizing. Table 2-1 shows the cases and sizing.

Table 2-1 Control Valve Cases

	case 1	case 2
P1 (bar)	120	30
P2 (bar)	60	23
P3 (bar)	9	5
mass flow rate (kg/s)	30	3



Flow coefficient, C_v is used to define the valve capacity which represents the number of standard cubic meters of air (air at standard pressure and temperature) per minute that can flow through the valve at a pressure drop of one psi. C_v is defined as;

$$C_v = \frac{q}{NP} \left(\frac{TS_g}{x} \right)^{0.5} \quad (2.16)$$

Where q is the volumetric flow rate, P and T represent the upstream pressure and temperature respectively. S_g is the specific gravity of a gas relative to air, which means for air $S_g=1$. N is a constant value depends on the selected unit system. x is defined as pressure drop ratio.

$$x = \frac{P_{upstream} - P_{downstream}}{P_{upstream}} \quad (2.17)$$

It should be noted that the maximum flow coefficient is obtained when the valve is in a fully open position. However, intermediate flow coefficients can also be determined.

Flow coefficient calculation is carried out for cases 1 and 2 indicated in Table 2-1 and maximum flow coefficient values with a safety factor for the first and second valve are found to be 300 and 340, respectively. In reference [8] more information can be found about valve sizing in a direct connected test facility.

The diameter of a equal percentage valves having flow coefficients of 300 to 340 are in order of 10 inch so that the valve diameter is selected as 10 inch. Piping is also selected to have the same diameter as the valves.

To fill up the air tanks, a high capacity compressor is needed. Most common types of compressors in use today are; piston compressors, rotary screw compressors, rotary sliding vane compressor and centrifugal compressors. Piston compressor stands out with the capability of supplying almost constant mass flow rates at high pressures up to 120 bar. Total air mass requirement coming from the capacity of the air storage tank is about 2600 kg. If the objective is selected as filling the tank in one day maximum, then compressor mass flow rate is;

$$\dot{m} = \frac{2600 \text{ kg}}{(24 \cdot 60 \cdot 60)s} = 0.03 \text{ kg/s}$$

2.3 Air Heater System

If the maximum required temperature is 1000 K and required temperature rise is higher than 700 K, the power of the air heater can be evaluated as;

$$P_{air\ heater} = \dot{m}C_p(T_2 - T_1) = (10\text{kg/s})(1006\text{J/kgK})(1000\text{K} - 288\text{K})$$

$$= 7.3\text{ MW}$$

The air heater is expected; to supply constant temperature (against the temperature drop at the at the inlet of the heater), should not be very large and should not pollute the air.

Air vitiator, pebble bed heater and arc heater (electric type) can be used to heat the air. However, arc heater is the one which is first eliminated due to the high power requirement. Similarly, pebble bed heater is eliminated since the required test duration is quite long. Despite the fact that vitiator pollutes the air (changes the contaminants of the air), it is the only choice. Hydrogen can be chosen as fuel of the vitiator to minimize the air contamination. But because of the handling concerns, methane (hydrocarbon) is preferred as fuel. In reference [17], the design of the air vitiator is explained. Vitiator needs oxygen and nitrogen feeding systems too. The oxygen feeding system is important to maintain the mole fraction of air at 21% after the vitiator while the nitrogen feeding system is used to purge the feeding lines after the test or in an emergency situation. Schematic view of the feeding system is given in Figure 2.1.

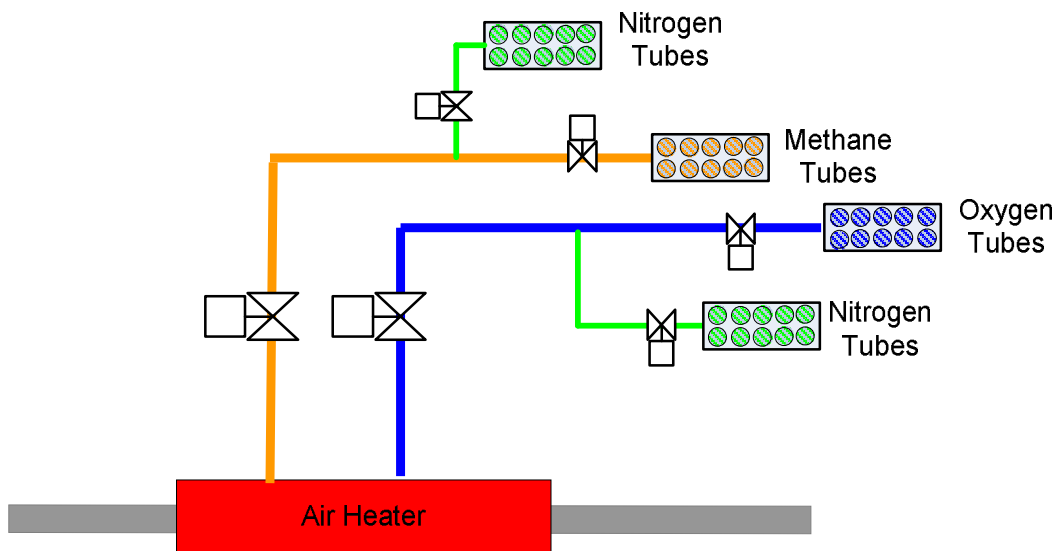
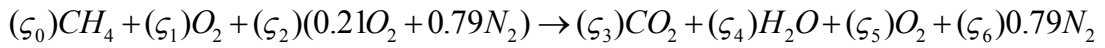
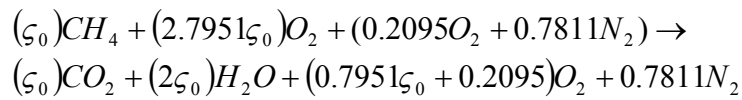


Figure 2.1 Schematic View Of The Feeding System

The required air mass flow rate is equivalent to the total of the air, methane and oxygen gases. Thus oxygen and methane mass flow rates should also be taken into account. Chemical reaction of the methane, replenishment oxygen and air is given as;

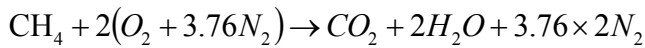


After the evaluation of the constants, the chemical reaction becomes,



By using enthalpy of fuel and replenishment oxygen for the required maximum mass flow rate of air and maximum temperature, the mass flow rates of the fuel and oxygen are calculated by assuming constant efficiency of the combustion. Mass flow rates, values of the fuel and oxygen mass flow rates are; 125 g/s and 600 g/s respectively. For the purging sequence, nitrogen mass flow rate requirement is selected as 600 g/s.

Stoichiometric combustion of the methane and air can be expressed as;



Air/fuel ratio can be calculated as;

$$(AFR)_{stoichiometric} = \frac{2(2 \cdot 16 \text{ g/mol} + 3.76 \cdot 2 \cdot 14 \text{ g/mol})}{1(12 \text{ g/mol} + 4 \cdot 1 \text{ g/mol})} = 17.16$$

Equivalence ratio ϕ is defined as;

$$\phi = \frac{(AFR)_{stoichiometric}}{(AFR)} \quad (2.18)$$

Equivalence ratio of the unity indicates that the air to fuel ratio is stoichiometric. Whenever the equivalence ratio is less than 1, the mixture of the fuel and air is lean or if the equivalence ratio is higher than 1, the mixture of the fuel and air is rich. In a gas

turbine combustion chamber, for a complete reaction, ϕ should be kept between 0.53-1.2 [17]. In our case, the equivalence ratio is about 0.2 which is under the stable combustion limit. Vitiator, which has certain a kind of bypass line as explained in reference [18], decreases the combustion limit up to an equivalence ratio of 0.2.

2.4 Control System

Mass flow rate and temperature of the air have to be maintained constant. This requirement is provided with three control mechanism. The first one is at the main line and controls the air mass flow rate. Second control loop controls the fuel flow according to the demanded temperature. Finally replenishment oxygen mass flow rate is regulated. Required oxygen mass flow rate is calculated from the fuel mass flow rate and this value is defined as the reference value. Control loops of the test facility is shown in Figure 2.2.

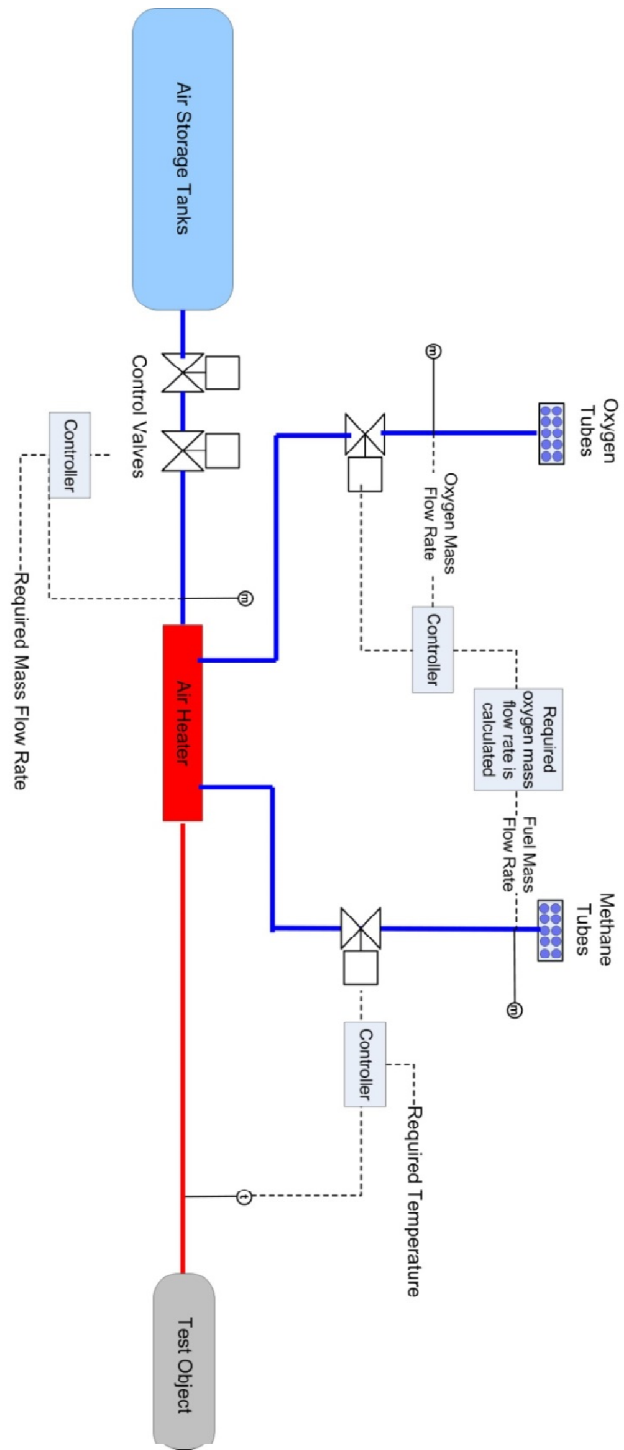


Figure 2.2 Control Loops

Controllers are simple Proportional, Integral Derivative (PID) controllers. Effects of the constants are shown in Figure 2.3 and Table 2-2. Controller constants are set by a trial and error method.

Table 2-2 PID controller constants [19]

	rise time	over shoot	settling time T_s	steady state error	stability
Increasing P	Decreases	Increases	Small Changes	Decreases	Decreases
Increasing K	Decreases a little	Increases	Decreases	Decreases	Decreases
Increasing D	Decreases a little	Decreases	Increases	Small Changes	Increases

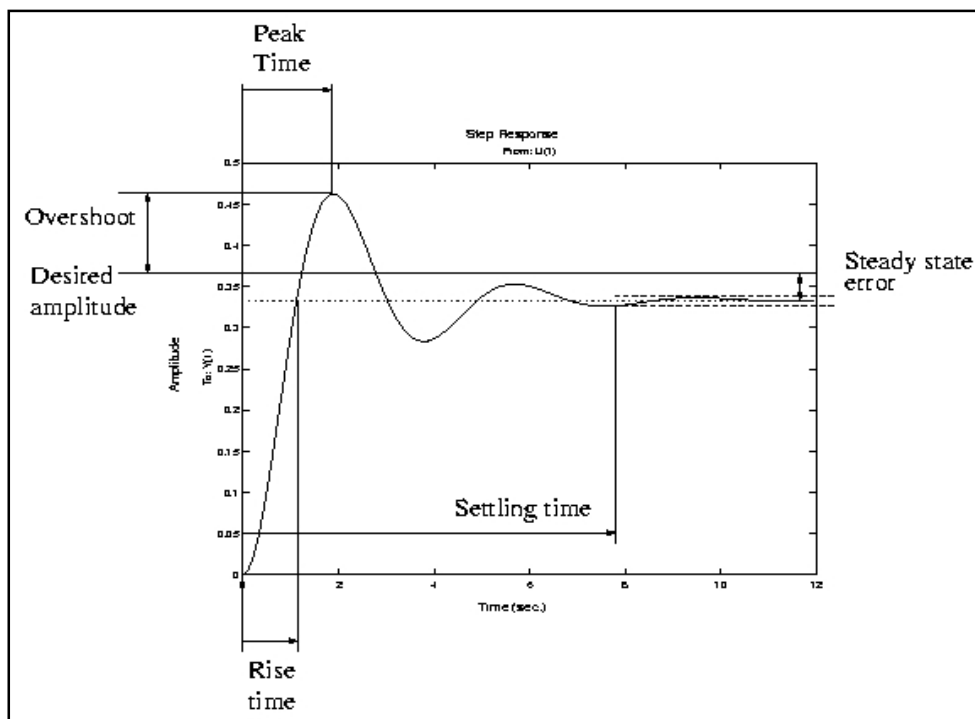


Figure 2.3 Step Respond Of a Generic System[19]

Control sequence of the direct connected test facility can be defined as follows;

- 1) Control valve is opened and air starts to flow. Opening fraction of the valve is a predefined value to supply required air mass flow rate.
- 2) Fuel and replenishment oxygen are given. Oxygen and fuel valve openings are similarly set to predefined values to maintain the required temperature.
- 3) Vitiator is ignited
- 4) After the air flow develops (where the required mass flow rate is achieved), controller of the main flow is activated to maintain the constant mass flow rate.
- 5) After the temperature rises to the required value, fuel and replenishment oxygen controllers are activated.

Predefined values (valve opening fractions), controller activation times and controller constants are determined by trial and error procedure. This trial and error is based on a numerical model which will be explained in Chapter 3. After this trial and error procedure on the numerical model, slight adjustments are made on the test facility.

Whole blowdown sequence is a transient event. But sequence is divided into to time period. Up to the settling time when flow is developing, line is pressurized. This time period is defined as fully transient. After the settling time of the test, although tank pressure is still decreasing and transient regime is still continuing, is defined as quasi steady state. Best time of ramjet combustor ignition is this quasi steady state regime.

2.5 Test Facility Interface

After the vitiator, a manifold to divide the lines into two for separate air intakes is used. The lines are connected to a second manifold which has a single degree of freedom at thrust vector. This single degree of freedom is provided by wheels. Manifold material is steel and thickness is calculated by using a safety factor of 4. Between first and second manifold groups, flexible hoses are used to maintain the moment freedom of second

manifold groups. The diameter of the flexible hoses is selected to ensure the safety factor of 4. The number of the flexible hoses is decided as 16 to maintain the Mach number under 0.3. The first and second manifold volumes are determined as 0.11 m^3 and 0.17 m^3 respectively to provide mechanical interface of flexible hoses. Schematic view of the interface is given in Figure 2.1.

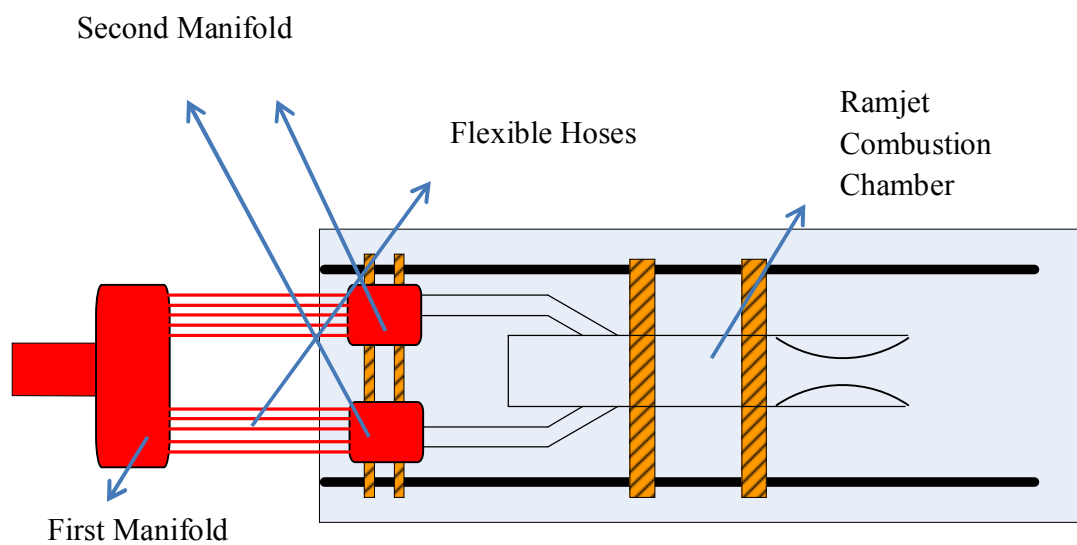


Figure 2.1 Schematic View of the Interface

CHAPTER 3

NUMERICAL MODELING OF DIRECT CONNECTED TEST FACILITY

3.1 NUMERICAL MODELING TOOL

Test facility contains lots of sub systems and sub components such as pipes, a combustion chamber (vitiator), valves etc. Modeling of the complete test facility with three or two dimensional computational fluid dynamics is not feasible. On the other hand, a system model is required at the design process for optimization and this system model is very useful to figure out the characteristics of the test facility. At this point, one dimensional numerical code Flownex is preferred, which is a commercial one dimensional CFD code. By using of this code, the capability of transient analysis of flow and heat transfer is acquired.

3.1.1 Flownex

Flownex solves the partial differential equations for mass, momentum and energy conservation to obtain the mass flow, pressure and temperature distributions throughout a network.

Three conservation laws govern the transport processes occurring in thermal-fluid networks and transport processes in general. These are:

- Conservation of *mass*.
- Conservation of *momentum*.
- Conservation of *energy*.

The various steps involved in the implicit pressure correction algorithm are shown in Figure 3.1[20].

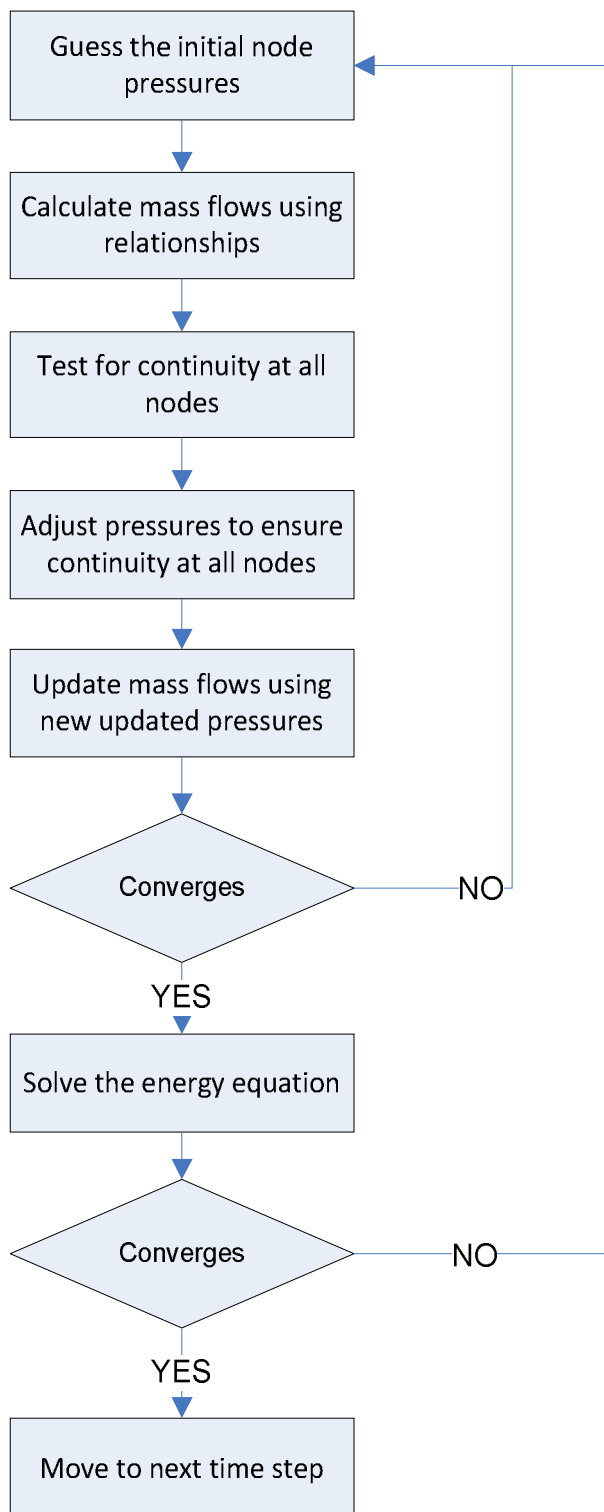


Figure 3.1 Flownex Solution Algorithm

3.1.2 Modeling of Components

Flownex model of the system is made by using elements such as pipes, control valves, orifices, heat transfer and adiabatic flame element. After and before the Flownex elements, there are nodes on which the calculations are performed. While modeling the whole system as one-dimensional, some simplifications are used. Brief explanations and modeling methodology of the elements are given as follows

3.1.2.1 Piping

Pressure loss of the pipe element is a function of friction factor, L/D and dynamic pressure. Δp is defined as;

$$p_{0i} - p_{0e} = \left(\frac{fl}{D} + \frac{\Delta T_0}{T_0} \right) \frac{p_0 \gamma M^2}{2} + \frac{p_0}{\rho} \left(\rho g \Delta z + K_i \frac{1}{2} \rho_i |V_i| V_i + K_e \frac{1}{2} \rho_e |V_e| V_e \right) + \frac{p_0 \rho L}{p} \frac{dV}{dt} \quad (3.1)$$

Where f is the friction factor, L and D is the length and the diameter of the pipe, ρ is the density of the fluid. V , V_i and V_e are the mean, inlet and outlet velocities of the fluid respectively. K_i and K_e are inlet and outlet loss coefficients of the pipe. Height difference is represented as $\Delta Z = Z_e - Z_i$ and $\Delta T_0 = T_{0e} - T_{0i}$ is used to indicate the total temperature difference. T_0 and p_0 are mean total temperature and mean total pressure respectively. γ is the ratio of specific heats of the fluid and M is the mean Mach Number in the pipe

The term with g represents the work done due to the elevation difference. Terms with K_i and K_e are used to calculate the inlet and exit pressure loss respectively. Three kind of pipe entrances are defined[21]. These are shown in Figure 3.2.

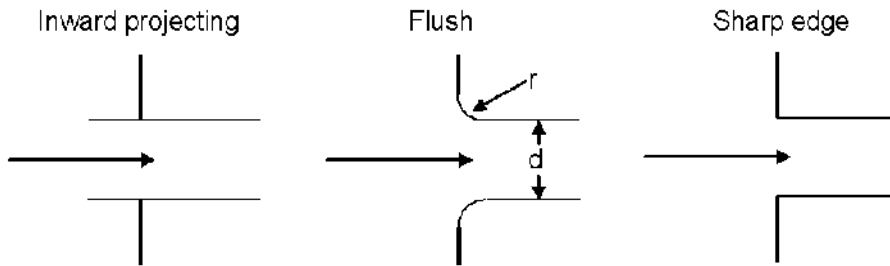


Figure 3.2 Pipe Entrance

At inward projection type and sharp edge type K parameters are; 0.78 and 0.5 respectively. K values of flush type entrance are defined as a function of r/d in Table 3-1[21].

Table 3-1 K values For Flush pipe Entrance

r/d	0.02	0.04	0.06	0.1	>0.15
K	0.28	0.24	0.15	0.09	0.04

Friction factor is found out by equation [21] set;

$$f(x) = \begin{cases} \frac{0.25}{[\log\{(e/3.7D) + 5.74/Re^{0.9}\}]^2}, & 5000 \leq Re \leq 10^8 \text{ and } 10^{-6} \leq \frac{e}{D} \leq 10^{-2} \\ \frac{64}{Re}, & Re < 2300 \end{cases} \quad (3.2)$$

In the region where $5000 > Re > 2300$ the friction factor is calculated with linear interpolation.

3.1.2.2 Control Valves

The equation below identifies the relationship between the mass flow rate, flow coefficients and the installation factor for control valves handling compressible fluids. The equation is valid for choked and non-choked laminar and turbulent flow.

$$\dot{m} = F_p C_v N_6 Y \sqrt{x P_1 \rho_1} \quad (3.3)$$

Where F_p is the piping geometry factor and N_6 is the numerical constant.

Expansion factor (Y) is a ratio of flow coefficient for a gas to that for a liquid at the same Reynolds

Number. The expansion [21] factor Y can then be expressed as:

$$Y = 1 - \left(\frac{x}{3 F_y X_T} \right) \quad (3.4)$$

Where X_T is the pressure drop ratio for the valve. The ratio of specific heats of a compressible fluid affects the flow rate through a valve.

$$F_y = \frac{\gamma}{1.4} \quad (3.5)$$

$$x = \frac{p_1 - p_2}{p_1} \quad (3.6)$$

Flownex uses two look-up tables consisting of C_v and X_T values which corresponds to the opening fraction of the valve. C_v value represents the valve mass flow capacity at referred opening fraction and X_T value (pressure drop ratio factor) indicates the pressure drop ratio at which the compressible flow will start to choke the valve.

3.1.2.3 Restrictors (Orifices)

Pressure drop in compressible flow is defined as;

$$\Delta p_0 = p_{01} \left(1 - \frac{p}{p_{01}} \right) \quad (3.7)$$

Indicates that the pressure loss is equal to the dynamic pressure of the gas. Mass flow rate and Mach number at the throat is calculated by using isentropic relations as

$$\frac{p_s}{p_{01}} = \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{\frac{-\gamma}{\gamma - 1}} \quad (3.8)$$

$$\dot{m} = MA^* p_{01} \frac{\sqrt{\gamma}}{\sqrt{RT_{01}}} \left[1 + \frac{\gamma - 1}{2} M^2 \right]^{\frac{-(\gamma + 1)}{2(\gamma - 1)}} \quad (3.9)$$

$$M = \sqrt{\frac{2}{\gamma - 1} \left[\left(1 - \frac{\Delta p_0}{p_{01}} \right)^{\frac{1 - \gamma}{\gamma}} - 1 \right]} \quad (3.10)$$

If the Mach number calculated is greater than 1, it is set equal to 1, which implies that the restrictor is choked.

3.1.2.4 Heat Transfer

The heat transfer element is used to model heat transfer in solid structures. Heat transfer element handles the problem as shown in Figure 3.3. The convective heat transfer coefficients are constant throughout the heat transfer element and temperature distribution in a solid increment is linear.

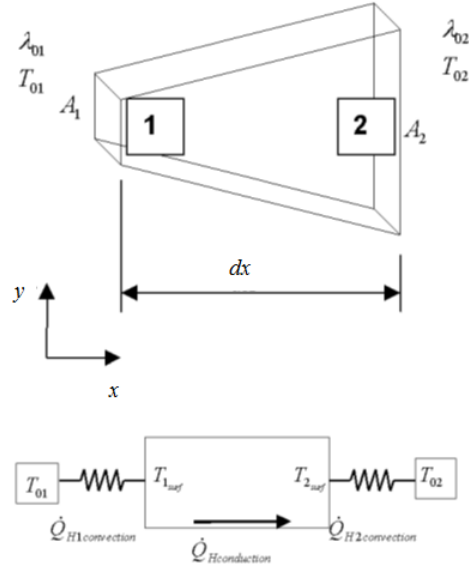


Figure 3.3 Heat Transfer Element

Heat transfer equations are given below;

$$\dot{Q}_{convection1} = h_{01}A_1(T_{01} - T_{1surf}) \quad (3.11)$$

$$\dot{Q}_{conduction} = \frac{k_x A}{dx} (T_{1surf} - T_{2surf}) \quad (3.12)$$

$$\dot{Q}_{convection2} = h_{02}A_2(T_{2surf} - T_{02}) \quad (3.13)$$

Since radiation is not a major parameter for our case, this property is not mentioned here. Conduction coefficients are calculated from the material data base as a function of temperature. Convection coefficient is calculated by calculation of Nusselt number. Nusselt number is taken constant when there is a zero and laminar flow for which the Reynolds number is less than 2300. For turbulent flow Nusselt number is calculated by Dittus-Boelter type correlation [21]. Dittus-Boelter correlation is defined as;

$$Nu (trubulent) = C Re^m Pr^n \text{Reynolds Number} > 5000 \quad (3.14)$$

Where C is 0.023 and m is 0.8. n is 0.4 or 0.3 according to the fluid heating or fluid cooling case respectively.

Nusselt number for transitional cases which Reynolds number is between 2300 and 5000 the following correlation[22]is used;

$$Nu = \frac{f/8(Re - 1000)Pr_1}{1 + 12.7\sqrt{\frac{f}{8}}\left(Pr_1^{2/3} - 1\right)} \left(\frac{Pr_1}{Pr_2}\right)^{0.11} \quad (3.15)$$

with

$$f = (1.82 \log Re) - 1.64 \quad (3.16)$$

Wheref is the friction factor of the pipe, Pr₁ and Pr₂ are Prandtl number evaluated at the fluid temperature and inner surface temperature of the pipe.

3.1.2.5 Adiabatic Flame

Combustion in vitiator is calculated by using adiabatic flame element. The Adiabatic Flame element calculates the off-gas composition and maximum temperature for a chemical reaction of a chemical mixture. Chemical reaction is solved by a secondary program, NASA Glenn Chemical Equilibrium Program CEA2 (the Gordon-McBride program) Flownex SE generates an input file (.inp) for the Gordon-McBride program, similar to the one presented below [21].

```

problem
  hp p,bar=1.00595918050396
react
  fuel=CH4 wt=0.098t,k=303.15
  fuel=O2 wt=0.902 t,k=303.15
  output mass short
end

```

Flownex SE populates the input file by retrieving the reaction pressure, inlet temperature and the mass fractions of the reactants with their reactant names from the upstream node. CEA2 program uses this Flownex SE generated input file to generate the

output file (.out). Flownex SE then retrieves the mass fractions of the reaction products and the off-gas temperature and returns it to the downstream node[21].

3.2 ONE DIMENSIONAL NUMERICAL MODEL OF DIRECT CONNECTED TEST FACILITY

Schematic view of the one dimensional numeric model of direct connected test facility designed in Chapter 2 is given in Figure 3.4.

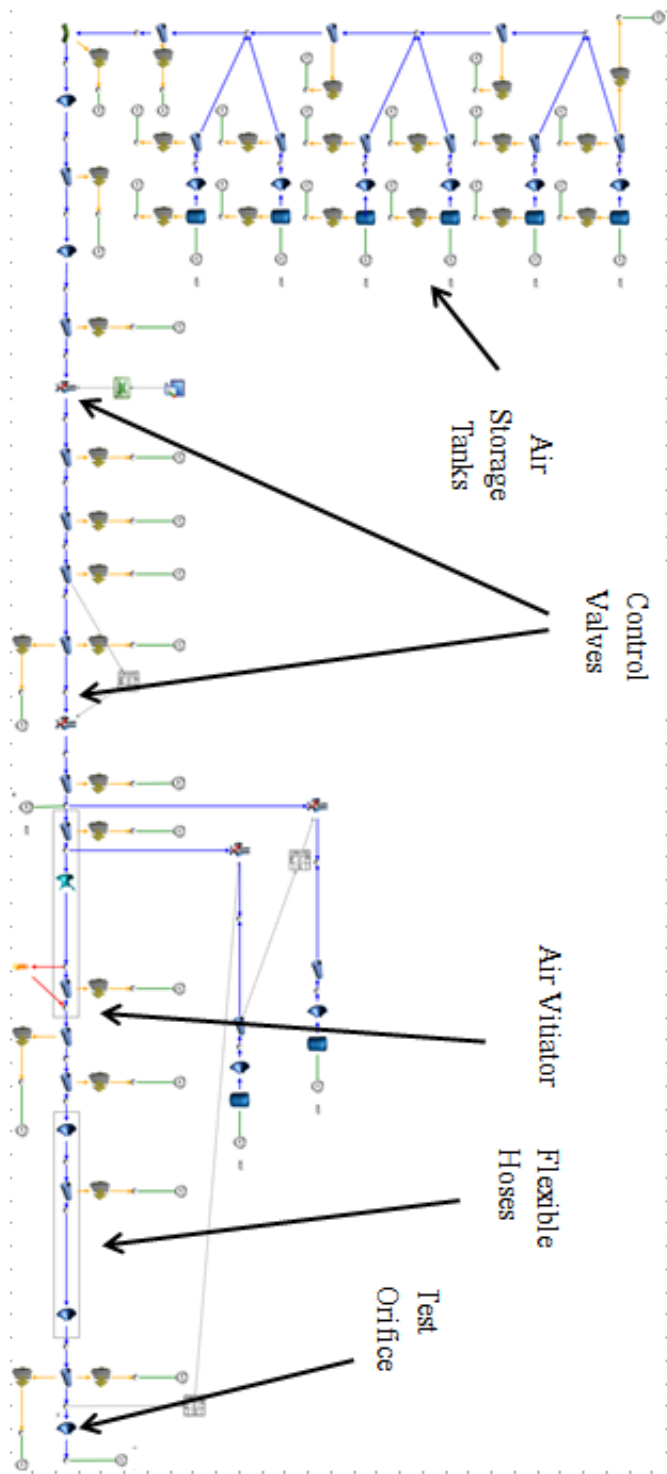


Figure 3.4 Schematic View Of The Direct Connected Test Facility

Each of the reservoirs is connected to the main line with an on-off valve. On the main line, a manual and an automatic on-off valve are mounted after the reservoirs. Position of the control valves are also shown in Figure 3.4. A venture mass flow meter is used for mass flow measurement between the two control valves. Downstream of the second control valve, air vitiator is placed with its fuel and replenishment oxygen feeding system. Before tests with ramjet engine test facility is tested standalone to qualify the sub systems and the whole test facility. These qualification tests are done by orifices placed at the end of the line. Orifices are important to simulate the ramjet engine. For example for the

Simulation of a Mach number 3 at an altitude of 10 000 m the required total temperature and total pressure is 625K and 9.7 bar, respectively, and mass flow requirement is 5kg/s. At qualification test (standalone test) to simulate the steady state condition (625K, 9.7 bar and 5kg/s) of the ramjet, an orifice should be used at the end of the line with an area A^* instead of being connected to the ramjet combustion chamber.

$$A^* = f(m, P_t, T_t) \quad (3.17)$$

Similarly for the validation of the numerical modal, orifices are used at the end of the line (at the end of the interface) and standalone tests are used for the validation.

Orifices requires a discharge coefficient as an input. To determine this value a control volume is selected which includes only the orifice and discharge coefficients are calculated by using the test results. Test results are shown in Table 3-2. Pressure and temperature values are transmitter values mounted in the second manifold group which are just upstream of the orifice.

Table 3-2 Determination of Orifice Discharge Coefficient

Test #	Pressure (bar)	Temperature (K)	Area (mm ²)	Cd
1	5	600	10	0.99
2	2	600	10	0.98
3	6	550	10	0.98
4	6	800	10	0.98

Pressure and the temperature values are static values in the plenum chambers but since the Mach number in the plenum chamber is less than 0.1 these values are taken as total pressure and total temperature. For each case pressure is;

$$\frac{p_t}{p} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}} > 1.893 \quad (3.18)$$

for the complete working condition for this reason

C_d is calculated by using choking condition assumptions. C_d is the ratio of theoretical mass flow rate and measured mass flow rate.

$$C_d = \dot{m}_{theoretical} / \dot{m}_{measured} \quad (3.19)$$

Theoretical mass flow rate is evaluated as;

$$\dot{m}_{theoretical} = aM\rho A \quad (3.20)$$

M is the Mach number which is one. a and ρ are sound speed and density which can be expressed in terms of pressure (p), temperature (T), specific heat ratio (γ) and gas constant (R).

$$a = \sqrt{\gamma RT} \quad (3.21)$$

$$\rho = p/RT \quad (3.22)$$

$$p = p_t / \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}} \quad (3.23)$$

$$T = T_t / \left(1 + \frac{\gamma - 1}{2} M^2\right) \quad (3.23)$$

As a result of these calculations C_d is selected as 0.98.

Numerical model of control valve uses C_v and X_t values of the valves. These values are defined in previous chapter. C_v values are generally supplied by the manufacturer. However X_t value is should be determined. An equation [23] is used to model selected control valve. Mass flow rates are found according to the equation set and X_T values which correspond to the Flownex calculation methods are calculated.

Mass flow rate relation is given by;

$$w = 0.39266 \frac{c_f A_v M}{\sqrt{\frac{M}{28.96} z T}} P_1 (Y(1 - 0.148 \times Y^2)) \quad (3.24)$$

$$A_v = 27.32 C_v \quad (3.25)$$

Where w is the mass flow rate in kg/hr. A_v is the flow coefficient in terms of SI. M is the molecular weight. z is the compressibility factor for the valve inlet. c_f is a correction factor depends on the valve type and model and is given by

$$c_f = 0.9929 - 2.805 f_o + 6.916 f_o^2 - 7.639 f_o^3 + 3.030 f_o^4 \quad (3.26)$$

Where f_o is the opening fraction of the valve.

$$y = \frac{1.63}{C_f} \sqrt{\frac{P_1 - P_2}{P_1}} \quad (3.27)$$

$$Y = \begin{cases} y, & y < \frac{3}{2} \\ \frac{3}{2}, & x \geq \frac{3}{2} \end{cases} \quad (3.28)$$

Secondly X_t values are calibrated by using the same methodology used in C_d determination. A control volume is selected and test values are used. For X_t values of the control valve p_1 and p_2 are set as the boundary conditions on the Flownex model and X_t values are determined by trial and error. Afterwards variation of the X_t with the valve opening fraction can be determined.

Piping in the complete test facility is achieved by fitting the pipes to each other with flanges as shown in Figure 3.5. Thus for whole model piping loss coefficient (pipe entrance) is taken as a sharp edge type.

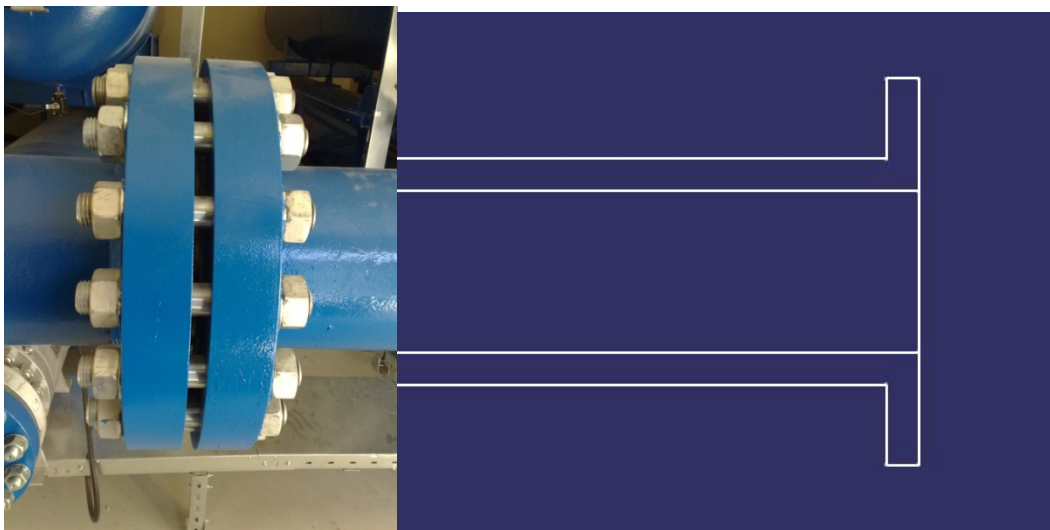


Figure 3.5 Piping connections

Heat transfer is taken into account with conduction and convection. Heat transfer element is used on every flow element in the model. In the heat transfer element, conduction problems are solved by using the thermal conductivity as a function of temperature and convection coefficient is calculated from a function of Prandtl and Reynolds numbers mentioned in the previous section. But for zero flow elements such as air storage tanks, zero flow Nusselt number is taken as 4 initially which is the default number in Flownex. After a trial and error process, zero Nusselt number is changed to adapt the temperature values. For the natural convection at the exterior surface of the pipes and air storage tanks, heat transfer coefficient is taken constant as $15 \text{ W/m}^2\text{K}$.

Temperature data is taken on the test facility by thermocouples. But thermocouples especially after the air vitiator (at hot region) are not inserted directly to the line cause of sealing. To ensure the sealing of pressurized lines thermocouples are used shown in Figure 3.6.

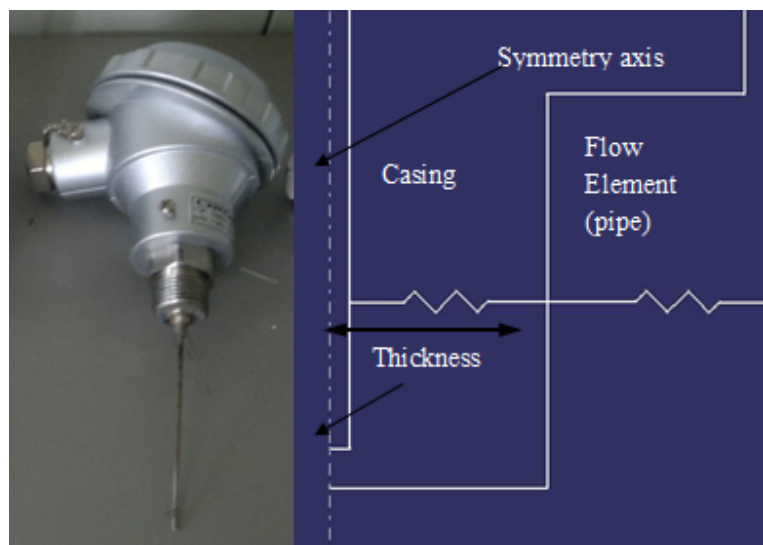


Figure 3.6 Thermocouple Model

These thermocouples are good for steady state measurements but for highly dynamic cases, the casing of the thermocouples creates a thermal capacitance and increases the response time. During the validation of simulation data with the test data, this effect

must be taken into account. The simulation data is directly compared with the test data. To resolve this situation, thermocouple is also modeled as shown in Figure 3.7.

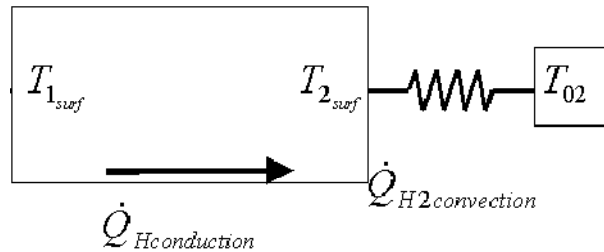


Figure 3.7 Thermocouple Model

Calibration of thermocouple model is done after the whole system model is done by fine tuning the “Thickness”. Two temperature data is presented in the simulation. One is the "Real Temperature" data which represents the instant temperature of the air. The second data represents the output value of the “Thermocouple Model”. Data are shown in Chapter 4.

Reaction on the vitiator is modeled as zero dimensional with the CEA2 code. Mixture ratio (air to fuel ratio) value and the total temperature value of the upstream node is used to calculate the adiabatic temperature. This temperature value is used as the boundary condition for the downstream node. Vitiator also creates the pressure drop because of its sub components (flame holding mechanisms, etc.). This pressure drop is modeled by using element of “restricted with loss coefficient” which is shown in

Figure 3.8.

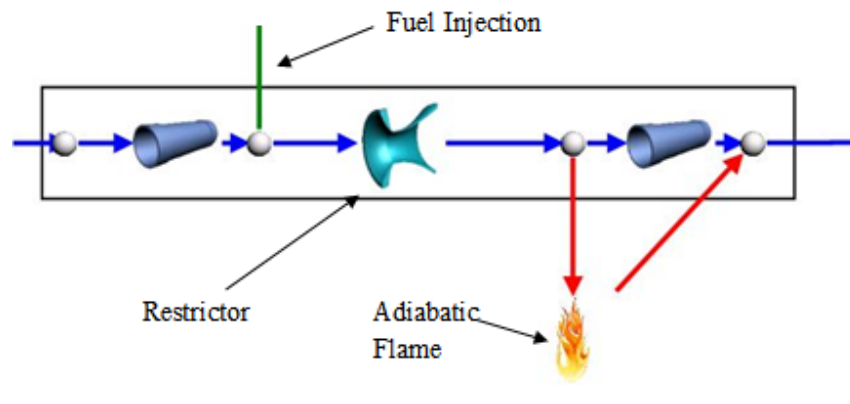


Figure 3.8 Air Vitiator Model

“Restrictor” element creates pressure drop which is equal to the dynamic pressure of the flow. Thus calibration tests are used to find out the appropriate diameter value. In Table 3-3, test results are shown. Last column shows the calculated value of the diameter to create the mentioned dynamic pressure as pressure loss. These cases show that orifice diameter of 88mm is sufficient to simulate the pressure loss in vitiator.

Table 3-3 Pressure Loss Calibration Test Results

Test #	Pt (bar)	m (kg/s)	DP (bar)	Orifice Diameter (mm)
1	1.97	2.39	0.25	88
2	1.9	2.29	0.19	89
3	2.89	2.4	0.2	88
4	2.82	2.28	0.16	88
5	10.03	7.07	0.32	89

CHAPTER 4

VALIDATION OF THE NUMERICAL MODEL

Pressure, temperature and mass flow parameters are used to validate the direct connected test facility numeric model. In this chapter test results are presented together with simulation results.

Validation is performed by comparison of data of station 0, 1, 2, 3 and 4. At these points' temperature and pressure test data is available and mass flow rate is measured between two control valves. Station numbers are shown in Figure 4.1.

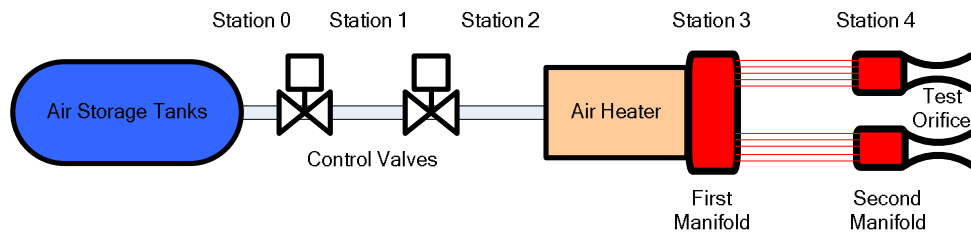


Figure 4.1 Direct Connected Test Facility Station Numbering

Station 0, represent the air storage tank values, station 1 and 2 are downstream of the first and second control valve. Downstream of the second control valve is used as the upstream of the air heater. Next pressure and temperature transmitters are mounted downstream of the air heater and at the end of line (upstream of the orifice).

4.1 TEST RESULTS

Tests used for validation are summarized in Table 4-1. The opening of the first control valve is presented by $t=0$ on time axis. Second control valve is already open (opening fraction is changed according to the test) so that the downstream of the first control valve is at ambient pressure initially. Pressurization of the line is starting with the opening of the first control valve at $t=0$.

Table 4-1 Validation Tests

Test #	Mass Flow Rate (kg/s)	Pressure (bar)
1	2.5	3
2	2.5	1.2
3	7	3

Error function is defined as

$$\% \text{ error} = \frac{|value_{test} - value_{simulation}|100}{value_{simulation}} \quad (4.1)$$

In Test#1 air storage tanks are pressurized to 46 bar absolute and the initial temperature in the tanks is about 15°C which is in ambient temperature. Test starts by opening control valve 1. Air vitiator is fired in tenth second and opening fractions of the control valves are not changed during the blowdown session. When the decrease in the tank pressure is equal to the 10 bar test is terminated by closing the first control valve.

Pressure values of the air storage tanks are plotted in Figure 4.2. Simulation and test data almost correspond to each other. There is quite a small and increasing error but still at the end of the simulation ($t=70$ second) maximum error is less than 0.5%.

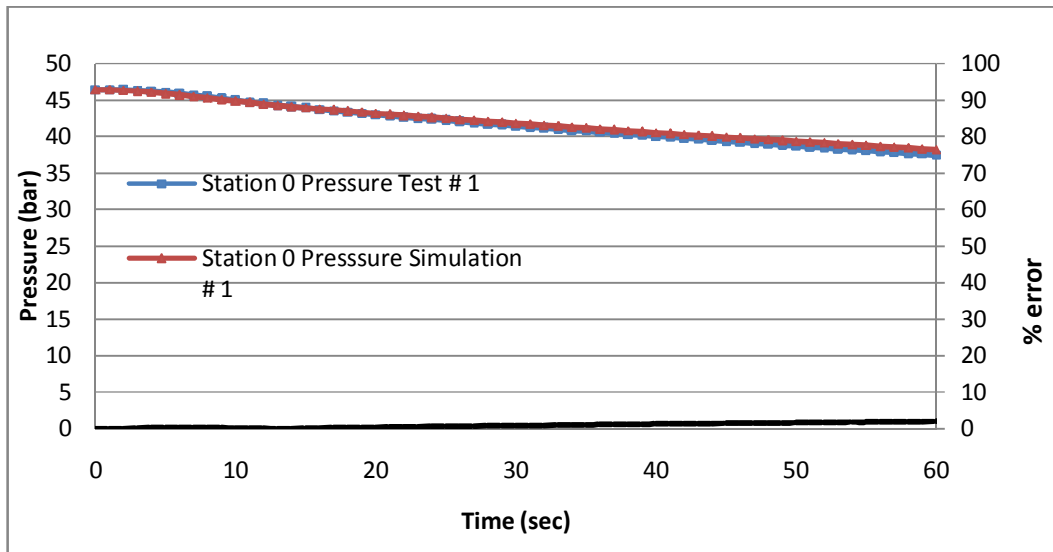


Figure 4.2 Comparison of Tank Pressure

Temperature data is also given in Figure 4.3. In this graph there are 2 simulation lines. First one (“Tank Temperature Simulation 1”) belongs to the air temperature. Second line belongs to the temperature of the thermocouple model which is described in Chapter 3.

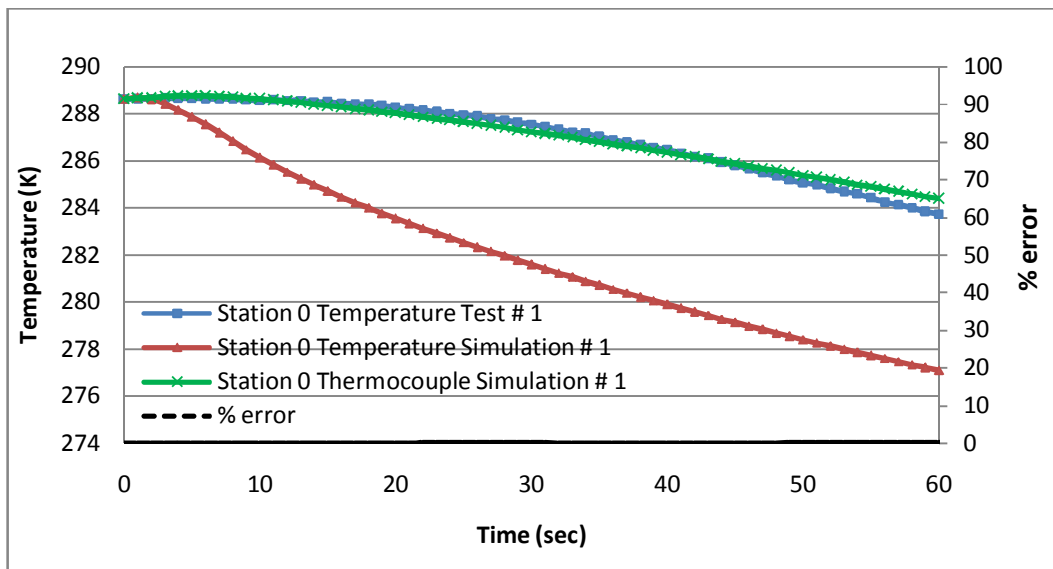


Figure 4.3 Tank Temperature Simulation and Test

This graph shows that there is reasonable difference between the real temperature value and the measurement of the thermocouple. To calculate the error on this parameter, test result and “simulation 2” is used. Error in temperature is maximum 6% in Celsius scale. Temperature error is larger than pressure error but it should be noted that error value consists of the effect of the thermocouple model.

Next comparison mass flow rate is given in Figure 4.4. Mass flow rate is increasing instantly and after settling time which corresponds to $t=20$ second, mass flow rate decreases according to the fall of air storage tank pressure.

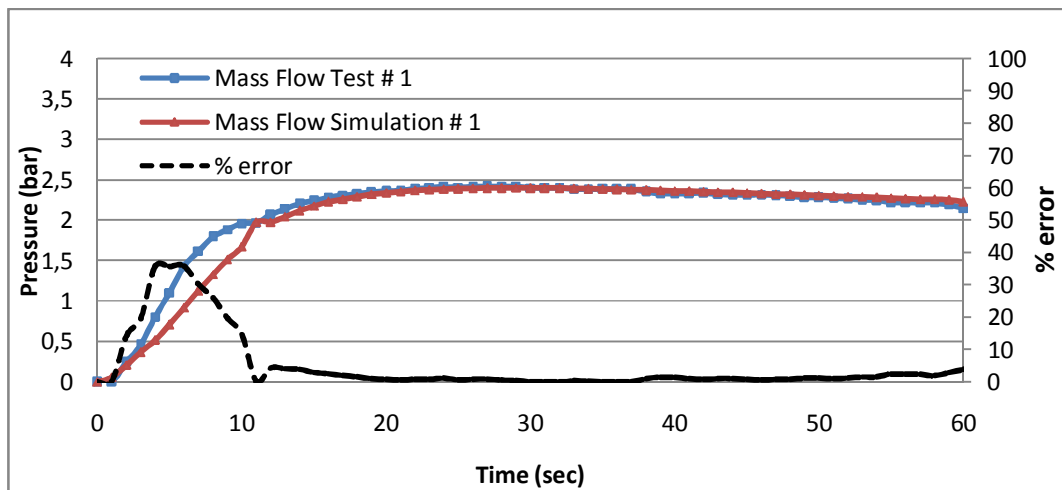


Figure 4.4 Mass Flow Rate

There is an error about 13% between fully transient period ($t=0$ to $t=10$). But after 10th second the error is down below 0.5%. Temperature data near to the mass flow meter (station 1) should be considered to explain the reason of the error. Temperature data is shown in Figure 4.5.

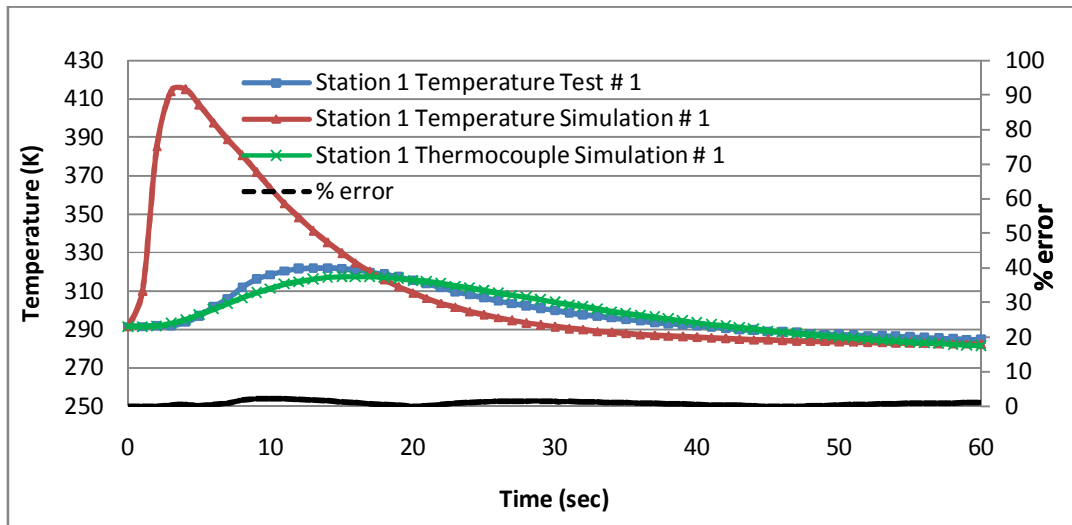


Figure 4.5 Station 1 Temperature Graph

Blue line represents the measured data. But it shouldn't be forgotten that this value is not the real temperature value on the line. Green line represents the thermocouple model. However red line shows the real, instant temperature value. This graph shows that temperature increases to 140°C in 3 seconds. After this point temperature decreases. Mass flow meter (venture mass flow meter) calculates the mass flow from the pressure, differential pressure and temperature value. But at this transient regime especially temperature data of mass flow meter may consist of measurement errors. Thus difference of 13% at simulation and test mass flow data is not considered as an error.

At $t=0$ all lines are pressurizing as mentioned before. Since second control valve restricts the flow, highest pressurizing (1 bar to 35 bar) is seen upstream of the second control valve (station 2). This pressurizing instant is shown in Figure 4.6 and also in temperature value in Figure 4.5.

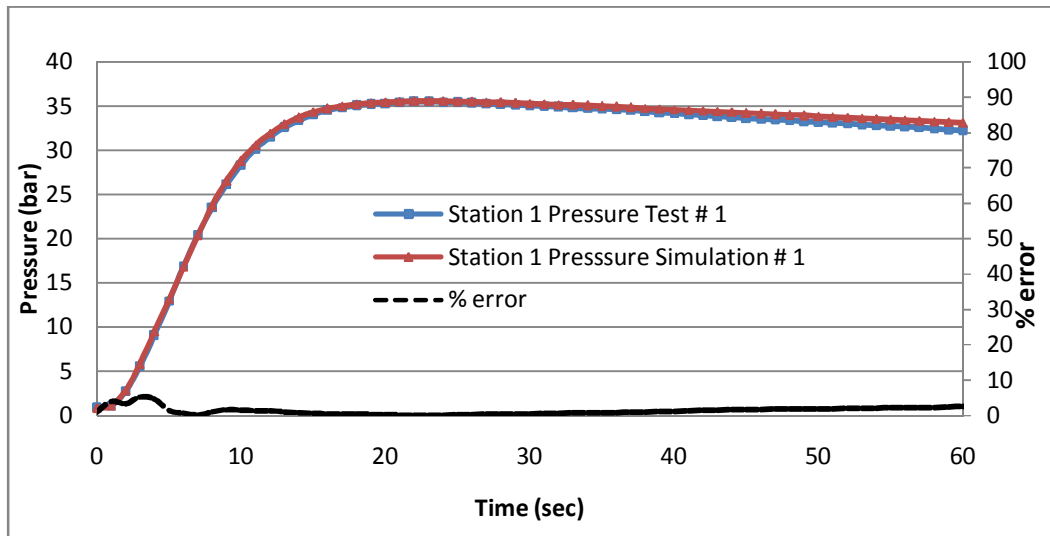


Figure 4.6 Station 1 Pressure Graph

At station 1, pressure data and simulation data correspond to each other with less than 2% error as shown in Figure 4.6.

Next station of the direct connected test facility is station 2, upstream of the air heater. Temperature and the pressure of the upstream conditions are given in Figure 4.7 and Figure 4.8. Pressure data corresponds to the simulation data in the steady state less than 1% error. At the transient regime maximum error is higher but still less than 0.2 bar which is acceptable.

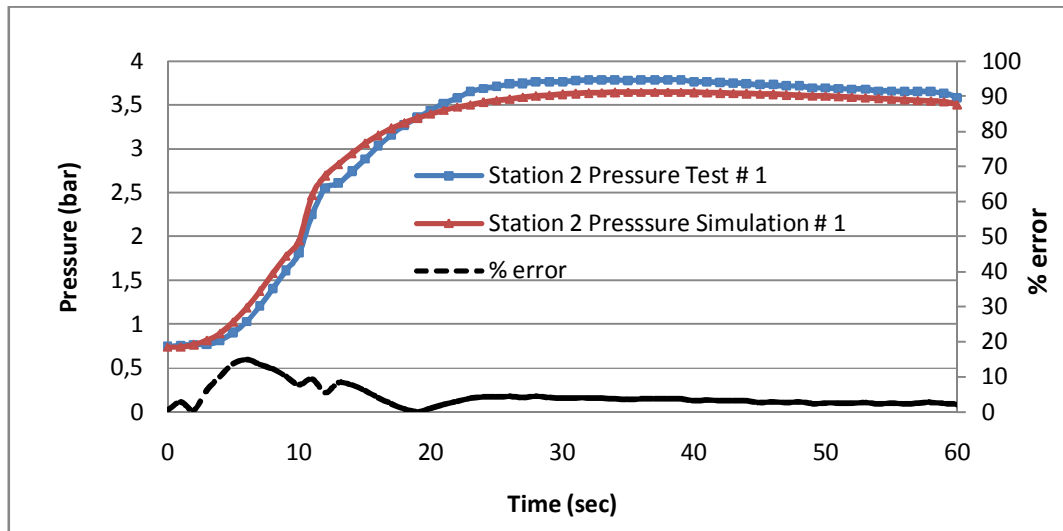


Figure 4.7 Station 2 Pressure Graph

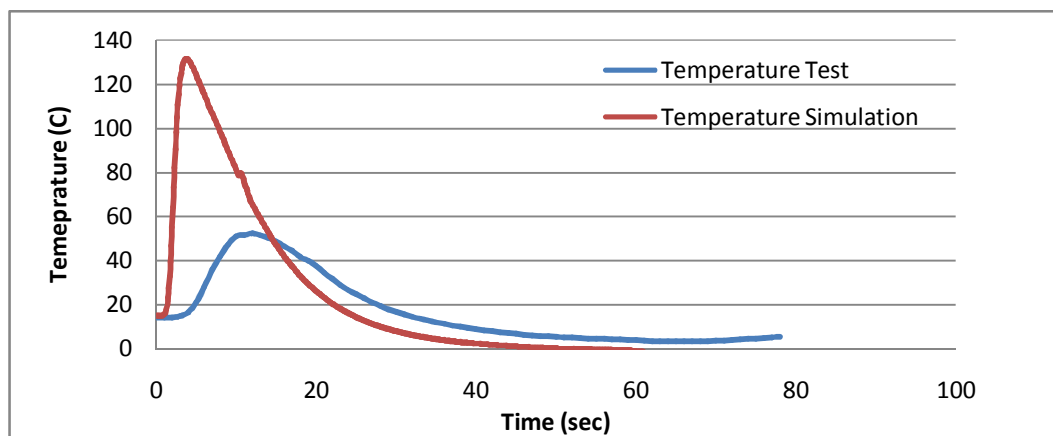


Figure 4.8 Station 2 Temperature Graph

Temperature data has a similar trend with the station 1 and decreases rapidly after the peak. At 10th second air heater is fired. This action can be seen on the pressure data as pressure increases and reflection of this situation can be seen in temperature (simulation data) as a discontinuity. Firing of the heater gives out the energy and increases the density. As result of this, pressure increases.

Because the thermocouple respond time is not enough, firing of the air heater is not seen in measured temperature.

In Figure 4.9 and Figure 4.10 pressure and temperature values are shown in station 4 with the simulation results. Temperature and pressure data satisfies the test results. After the firing of the air heater (vitiator), temperature increases instantly.

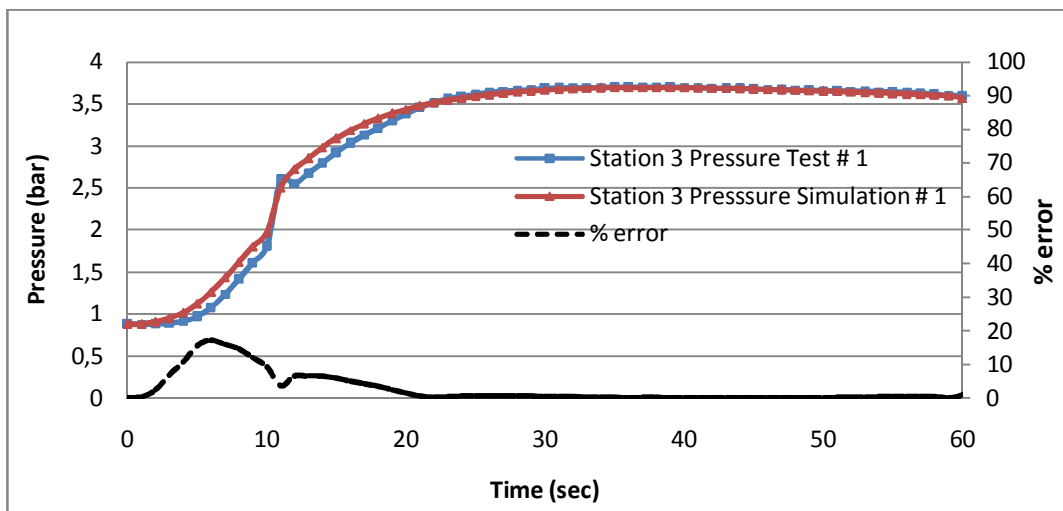


Figure 4.9 Station 3 Pressure Graph

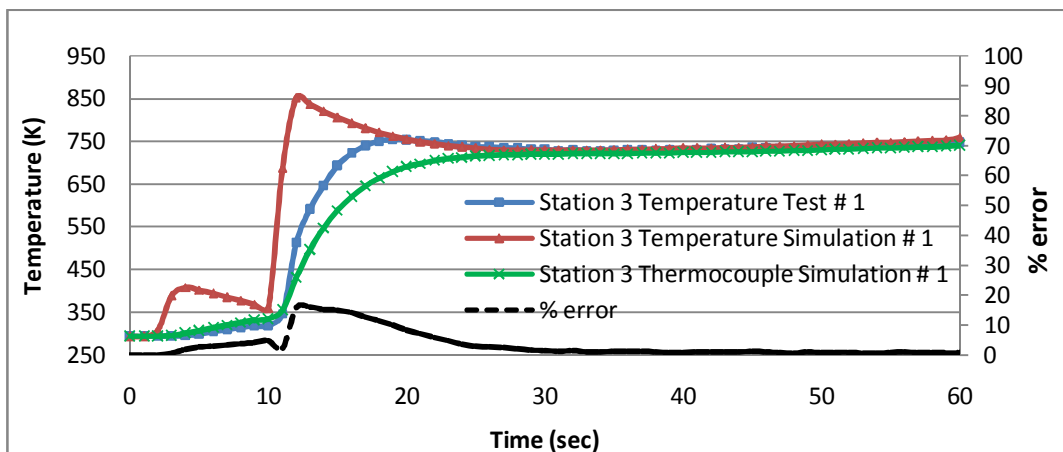


Figure 4.10 Station 3 Temperature Graph

Station 4 represents the end of the line which will be connected to ramjet engine. Thus this station is used to determine the flight condition. Pressure and temperature result of the station 4 is given in Figure 4.11 and Figure 4.12 respectively. Pressure and temperature results of the simulation data are satisfying in a similar trend with the previous stations.

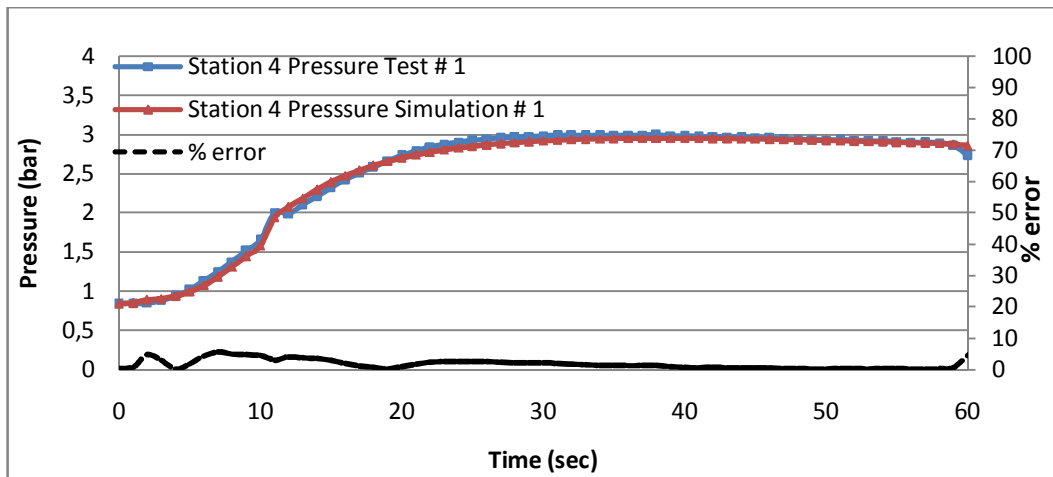


Figure 4.11 Station 4 Pressure Graph

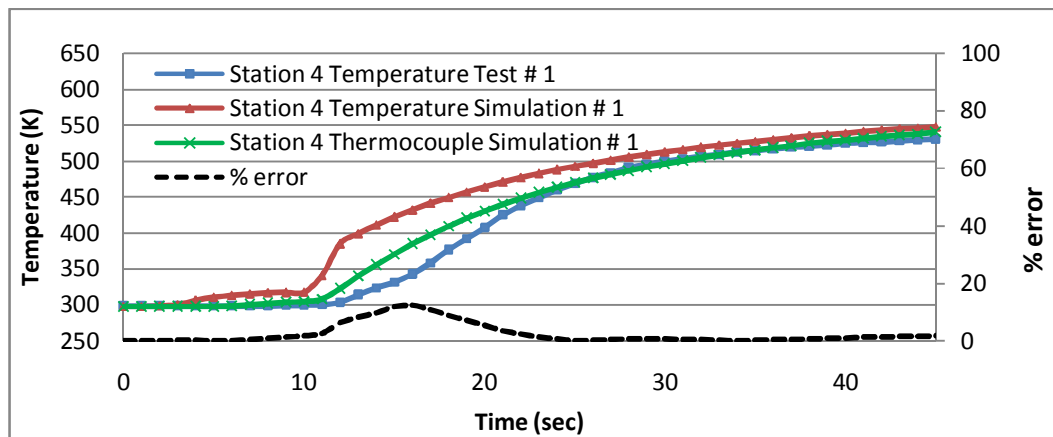


Figure 4.12 Station 4 Temperature Graph

In this test at the end of the line, pressure is almost constant during the blowdown. However temperature increases with almost the same acceleration. To explain this temperature rise temperature data is compared with the equivalence ratio (ϕ) in Figure 4.13.

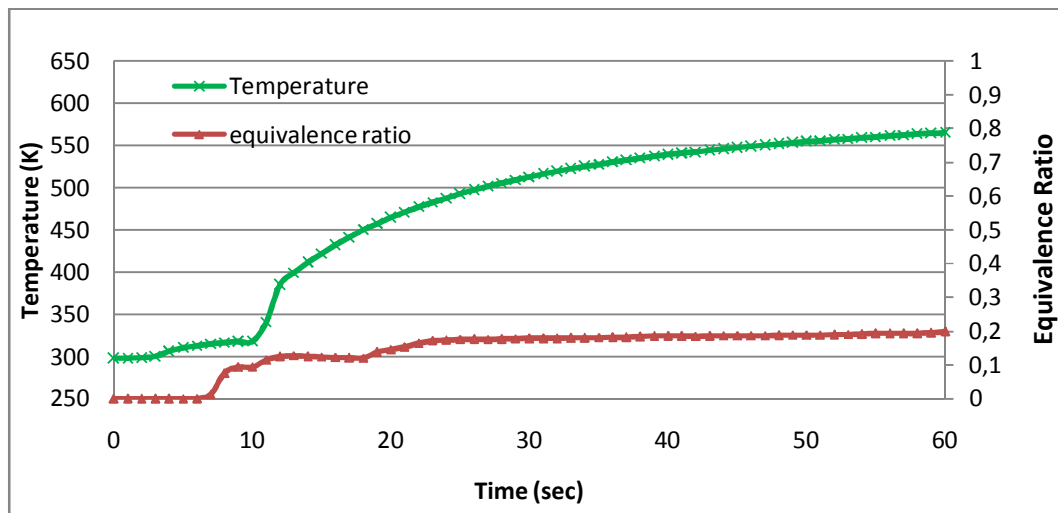


Figure 4.13 Temperature and Equivalence ratio

This graph shows that equivalence ratio in another words fuel mass flow rate is not responsible for this temperature rise. Secondly temperature of the station 3 is compared with station 4 in Figure 4.1.

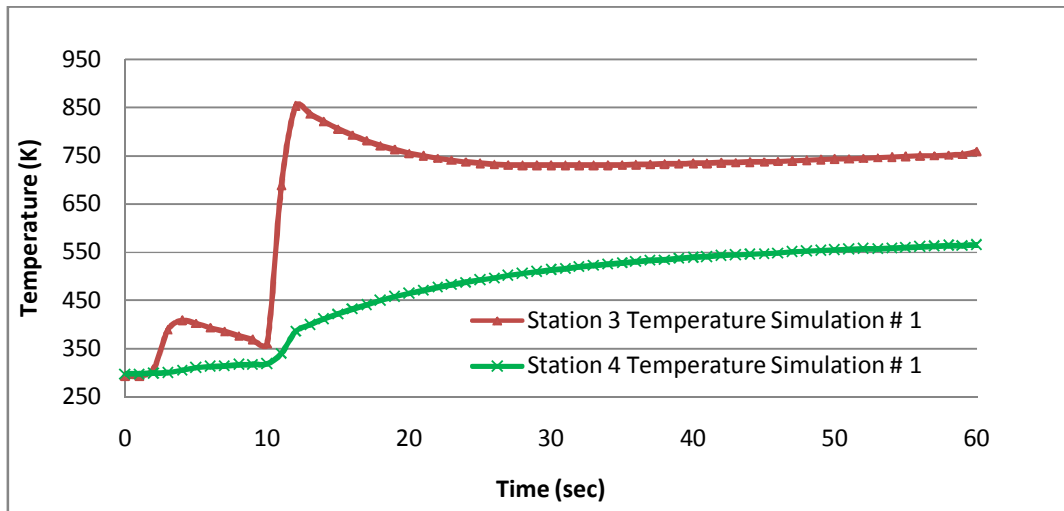


Figure 4.1 Temperature Of Station 3 and Station 4

Temperature value of the Station 3 is coherent with mass flow rate of the fuel. In this case temperature of station 4 is explained only with thermal inertia of the Test Facility Interface. Station 4 reaches thermally steady state condition at about 20th second; however, station 4 requires much more time to get to steady state condition. Heat loss from fluent is given in Figure 4.2. As seen in Figure 4.2 the deviation of the heat loss prevents the steady state regime.

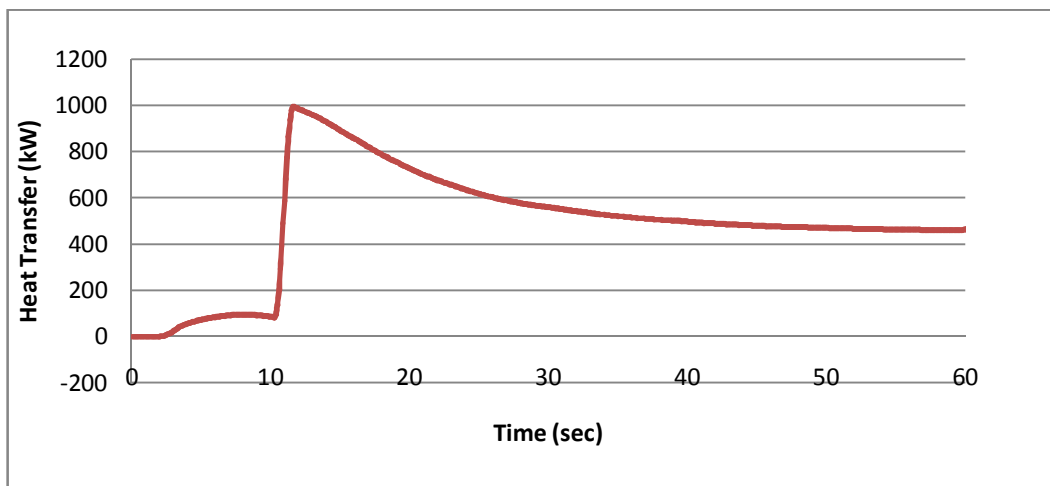


Figure 4.2 Heat Loss

This test is done for validation of simulation and ramjet engine is not integrated and fired. Test is done with orifice at the end of the line. In Chapter 2 methodology of finding combustion chamber total pressure (P_{t02}) and total temperature (T_{t02}) is explained. Even if the inverse of the calculations are done, Flight Mach number and altitude can be found.

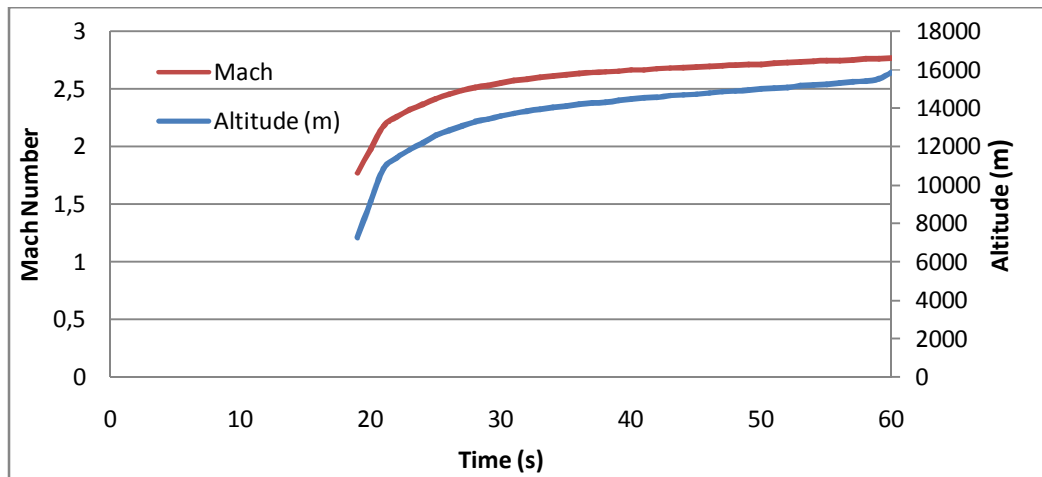


Figure 4.3 Mach Number and Altitude

Second validation test is done to figure out the effect of the pressure. Same test with the previous is replied with a larger orifice diameter. Thus, at the last station pressure is expected to be lower than the previous test. In Figure 4.4 and Figure 4.5 mass flow rates and pressure of air storage tank and upstream of the second control valve are given.

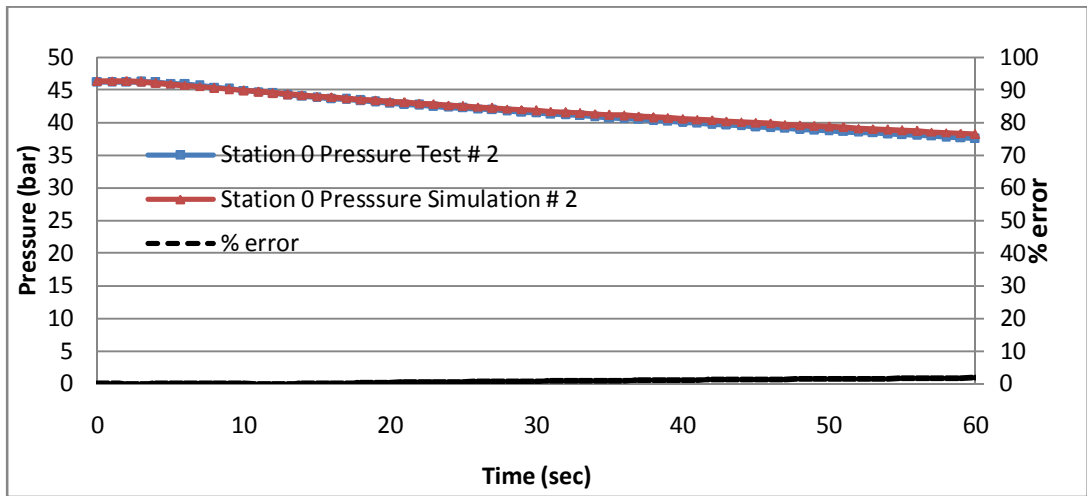


Figure 4.4 Air Storage Tank Pressure Graph

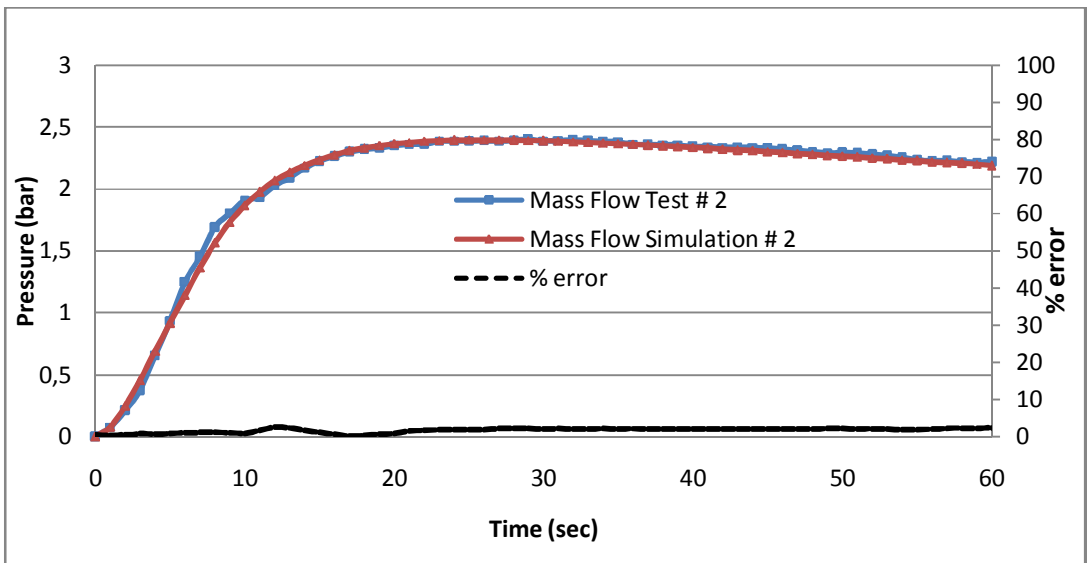


Figure 4.5 Mass flow rate Graph

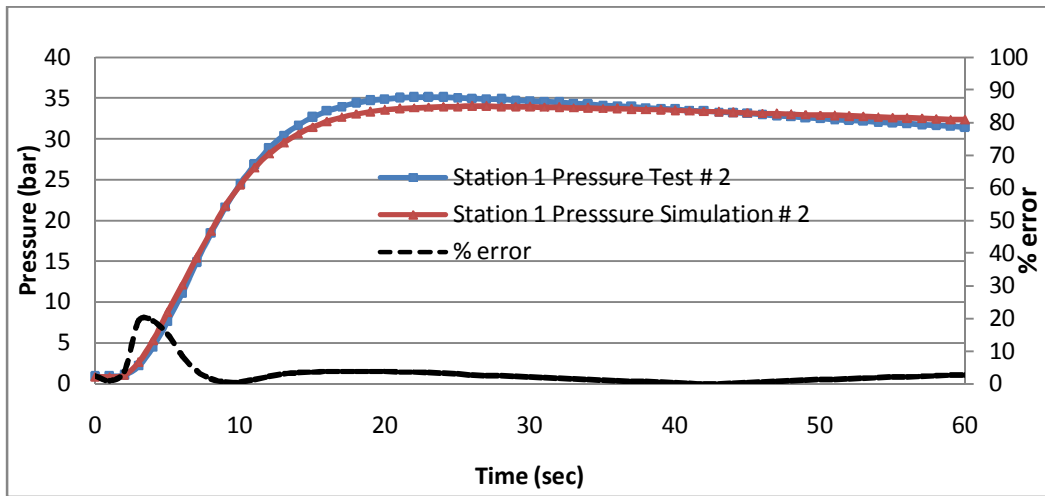


Figure 4.6 Station 1 Pressure Graph

The results of the temperature and pressure are exactly the same with the previous validation test, up to the second control valve. On the other hand, the results after the second control valve are quite different than the first test. Pressure and temperature results are shown in Figure 4.7, Figure 4.8, Figure 4.9, Figure 4.10 and Figure 4.11.

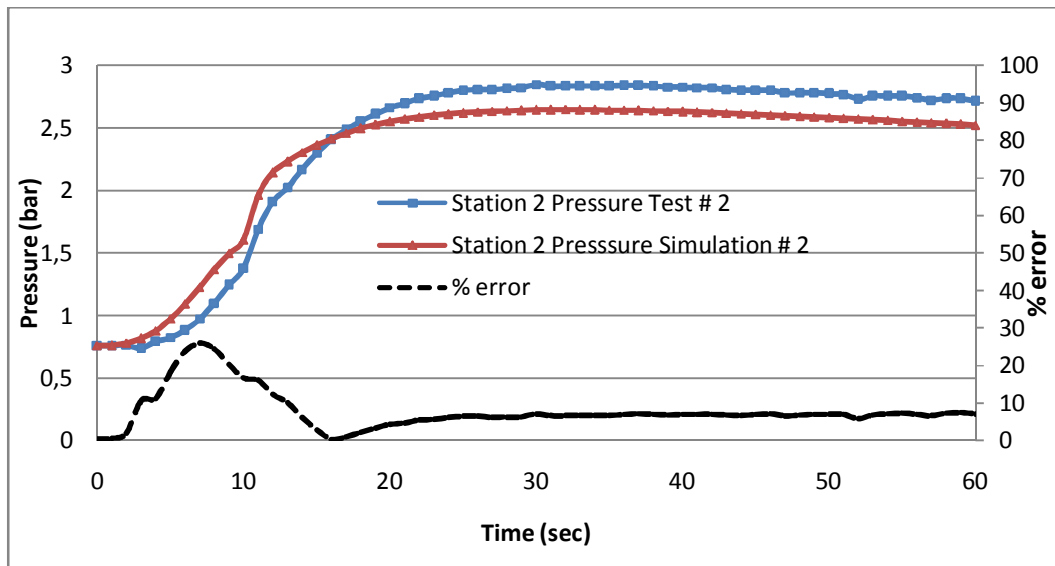


Figure 4.7 Station 2 Pressure

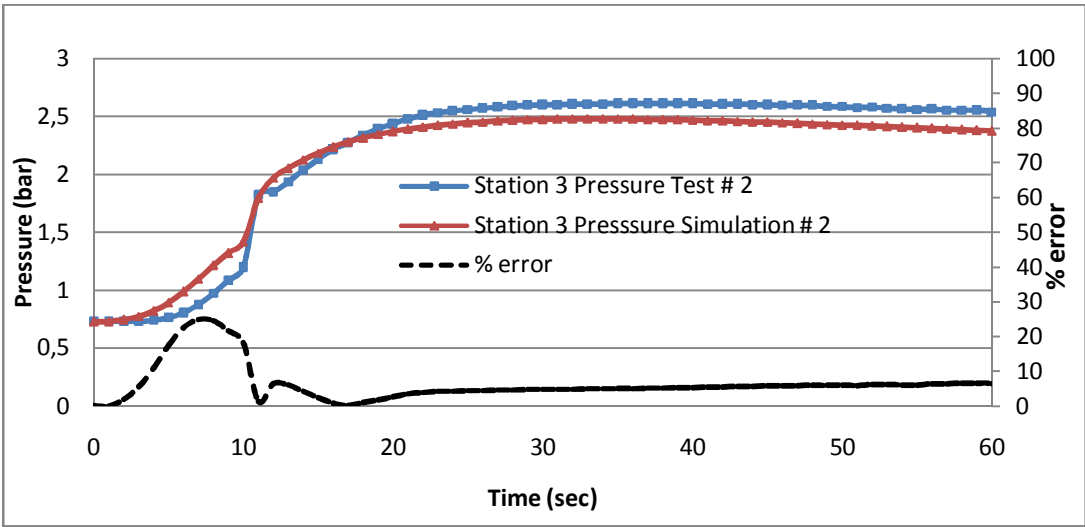


Figure 4.8 Station 3 Pressure

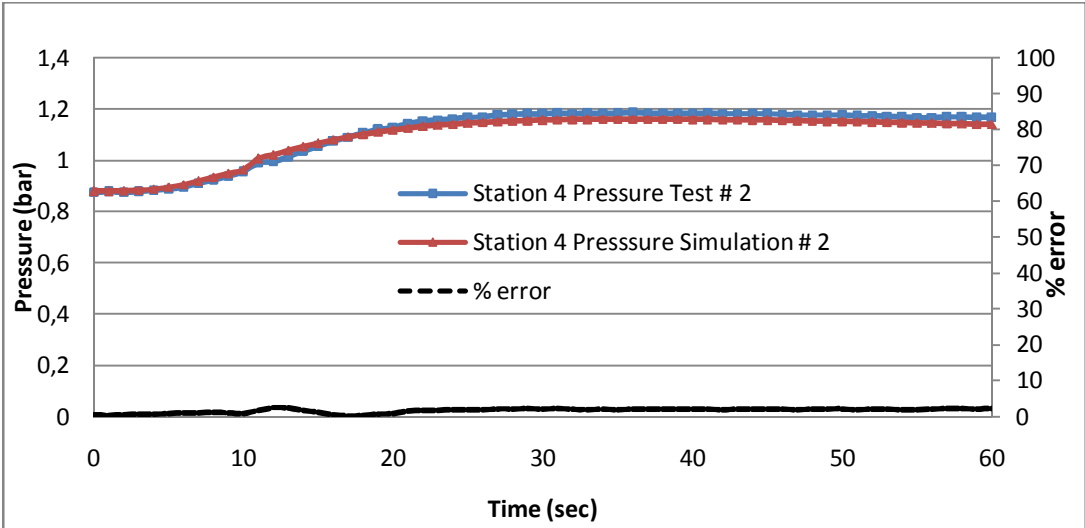


Figure 4.9 Station 4 Pressure

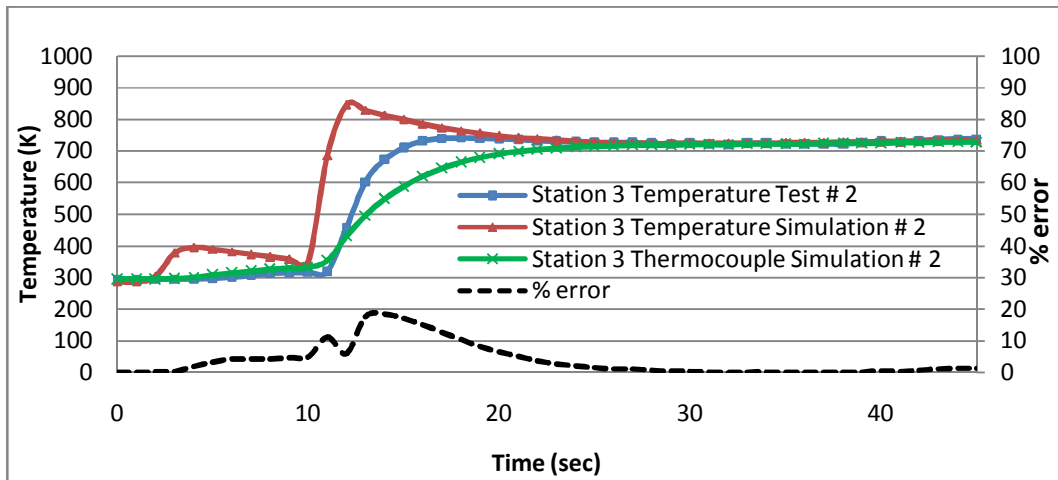


Figure 4.10 Station 3 Temperature

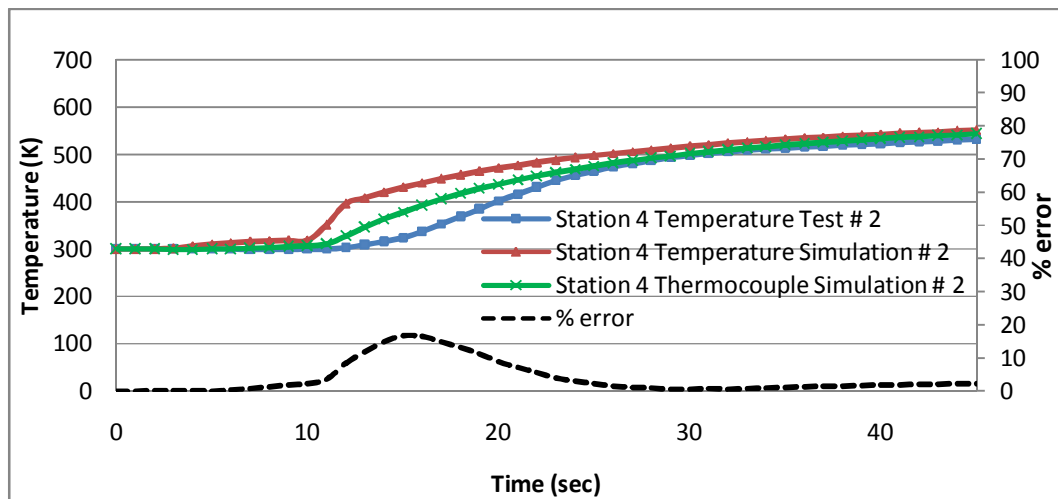


Figure 4.11 Station 4 Temperature

In this test case pressure ratio of the second control valve is higher than 20. Under this ratio second control valve is choked and isolates the information after the second control valve. Thus at the second test mass flow rate is not changed due to the change in orifice. Similarly since the fuel and air mass flow rates are not changed temperature does not change either.

Next validation test is performed with an initial tank pressure 120 bar. Air storage tank pressure and temperature are plotted in Figure 4.12 and Figure 4.13 respectively.

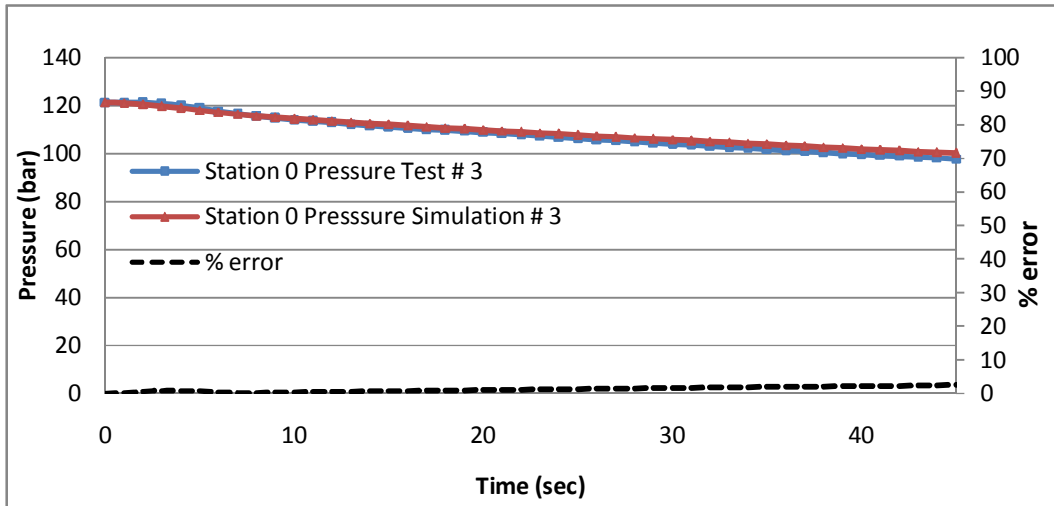


Figure 4.12 Station 0 Pressure

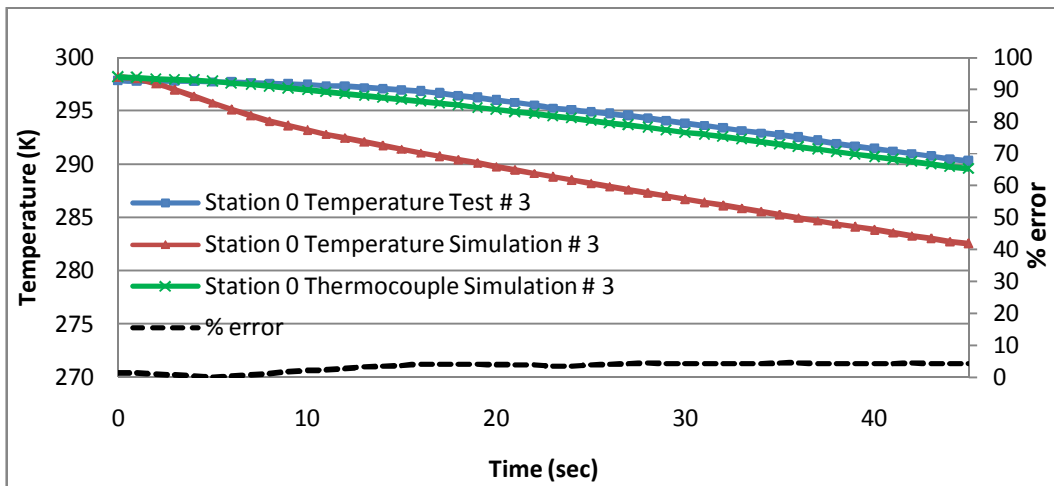


Figure 4.13 Station 0 Temperature

Error profiles are similar with the previous tests. In station 0, error of pressure is low but increasing linearly. Mass flow rate, pressure and temperature results of the middle stations are plotted in Figure 4.14, Figure 4.15, Figure 4.16 and Figure 4.17.

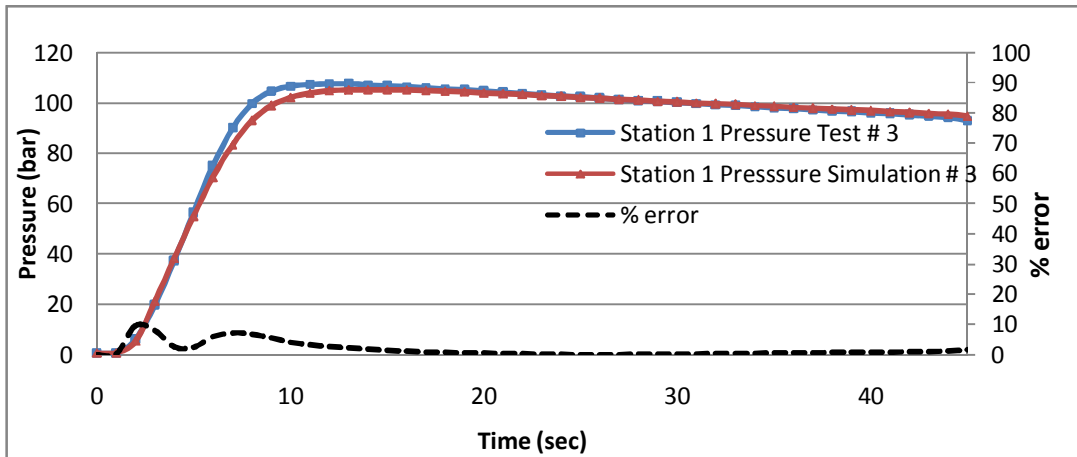


Figure 4.14 Station 1 Pressure

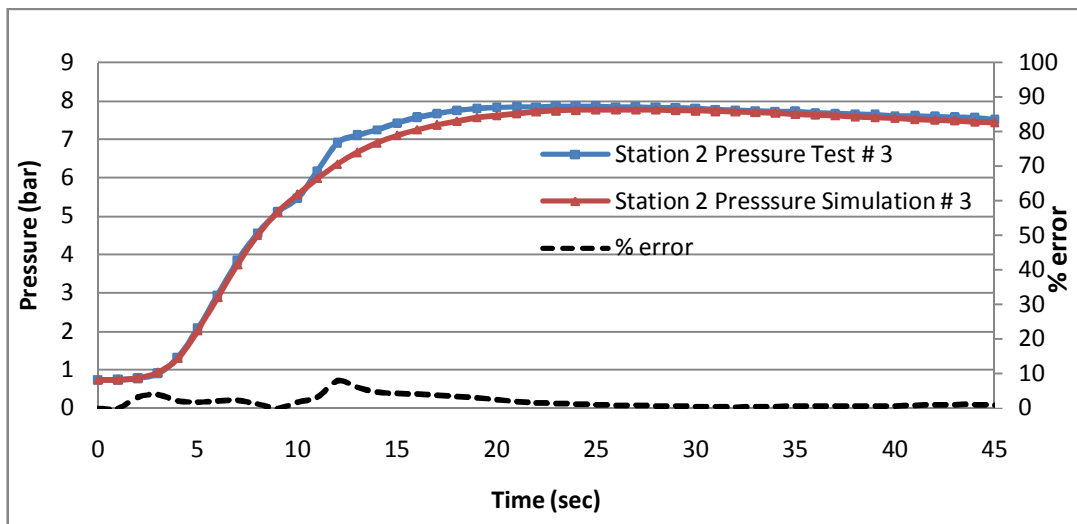


Figure 4.15 Station 2 Pressure

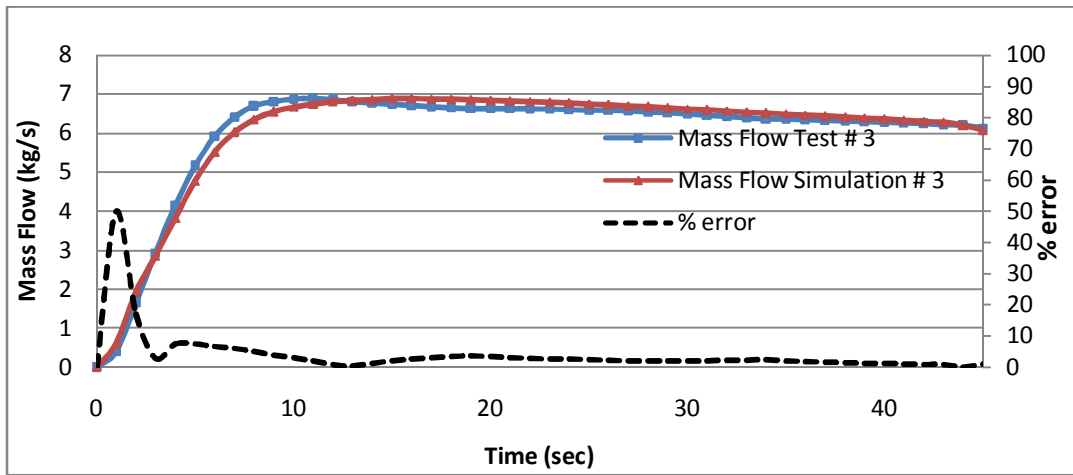


Figure 4.16 Mass Flow Rate

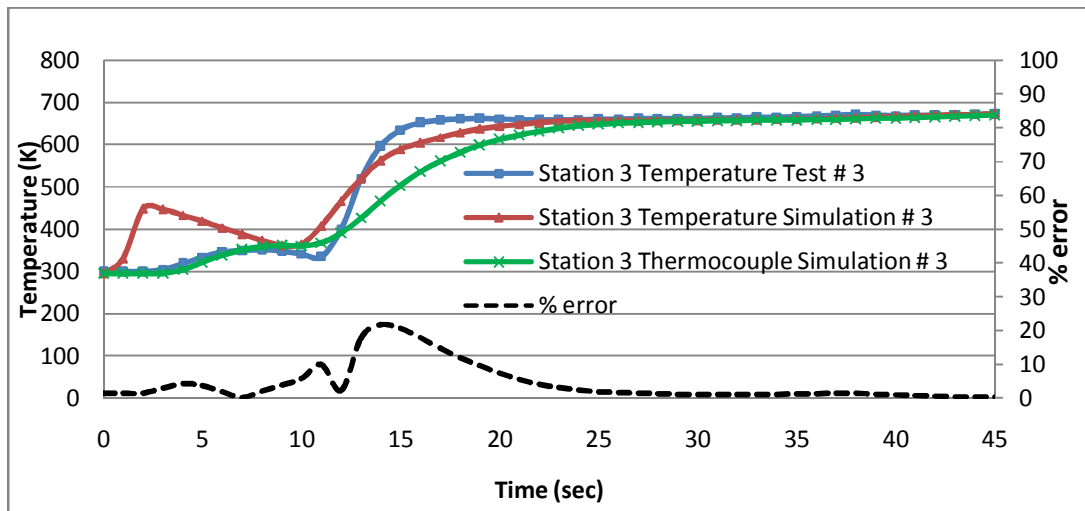


Figure 4.17 Station 3 Temperature

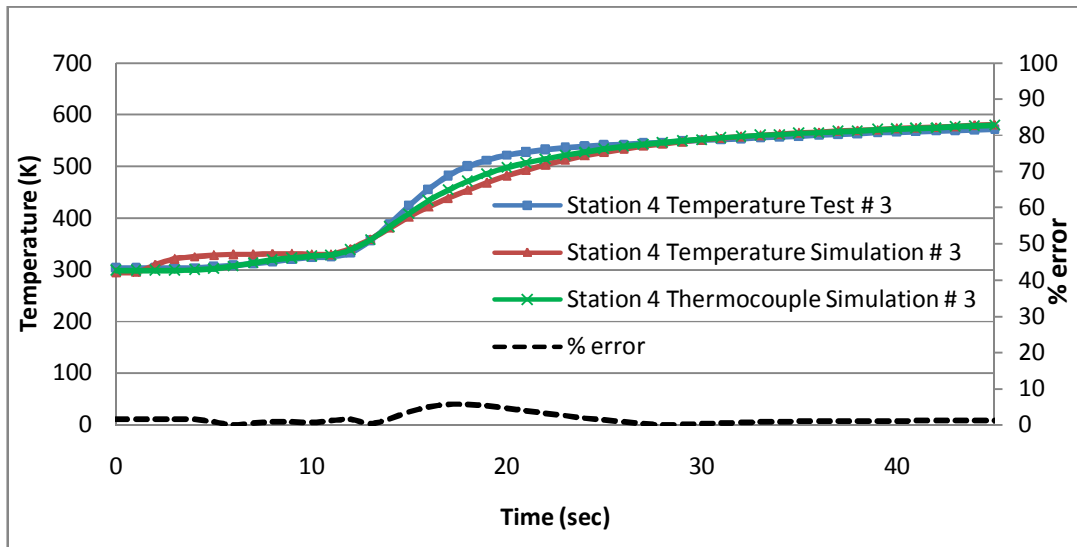


Figure 4.18 Station 4 Temperature

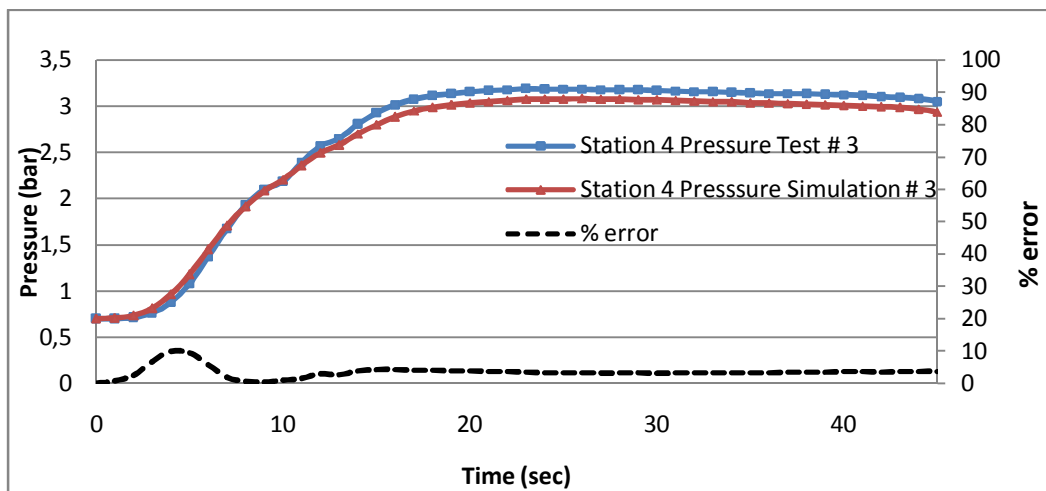


Figure 4.19 Station 4 Pressure

Validation tests shows that, numerical model can be used very effectively to determine the values of pressure temperature and mass flow rate at quasi steady state. At the quasi steady state phase maximum error is never exceed 10 percentage and in most cases error is less than 1 percentage.

CHAPTER 5

NUMERICAL MODEL APPLICATIONS

5.1 TEST PROCEDURE

To create a test case (flight simulation) on the test facility, several parameters have to be determined. These parameters are listed below;

Tank Initial Pressure; for the maximum air storage capacity, tanks should be pressurized to the maximum operating pressure. However in the cases where required mass flow rate is relatively low, control valve opening requirement may be unphysical. Thus initial tank pressure value may be lower than maximum operating pressure and has to be considered with the open fractions of the valves.

Control Valves Open Fraction; open fractions of the control valves have to be predetermined to maintain the required mass flow rates.

Flow Parameters; Flow Parameters consist of P,I,D constants. Control valves can be controlled by a PID controller or an opening profile can be defined on control valves.

A procedure has been established to determine these parameters by using the numerical model. Flow chart of the procedure is given in Figure 5.1. Flow chart consists two main iteration cycle. The first one is on the main line to maintain the required mass flow rate and the second one is to maintain the required temperature value.

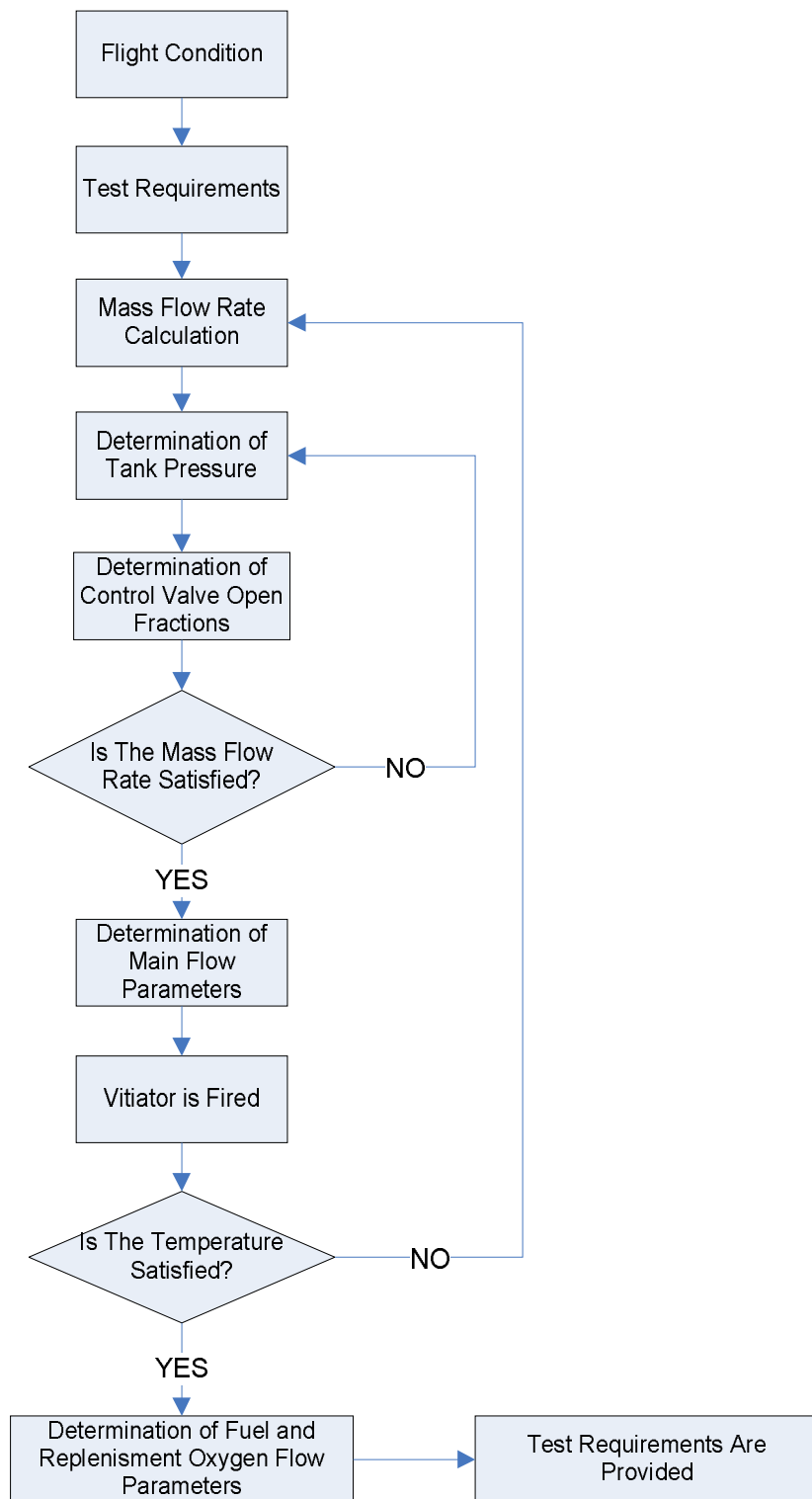


Figure 5.1 Simulation Flow Chart

This procedure is used on design condition of the test facility. Simulation conditions are given in Table 5-1.

Table 5-1 Simulation Condition

Flight Mach #	2
Flight Altitude (m)	0 (sea level)
Total Mass Flow Rate (kg/s)	10
Test duration (s)	120

In the second step total pressure and total temperature is found as 7.3bar and 518K respectively. Total mass flow rate requirement consists of air, methane and replenishment oxygen mass flow rates. Thus mass flow rates are calculated separately by using chemical reaction balance, mentioned in section 2.2.2. Mass flow rate results are shown in Table 5-2.

Table 5-2 Mass Flow Rates

Air Mass flow Rate (kg/s)	9,69
Methane Mass Flow rate (kg/s)	0,047
Replenishment Oxygen Mass Flow Rate (kg/s)	0,263
Total (kg/s)	10

The next step is the determination of boundary conditions of the air storage tank and open fractions of the control valves. Initially, boundary conditions are selected as 288K ambient temperature and maximum operating pressure as 120bar. Open fractions are configured to supply required mass flow rate at quasi steady state by trial and error method. Thus required mass flow rate is provided only by opening one step of the valves. Mass flow rate and open fractions of the control valves are plotted in Figure 5.2.

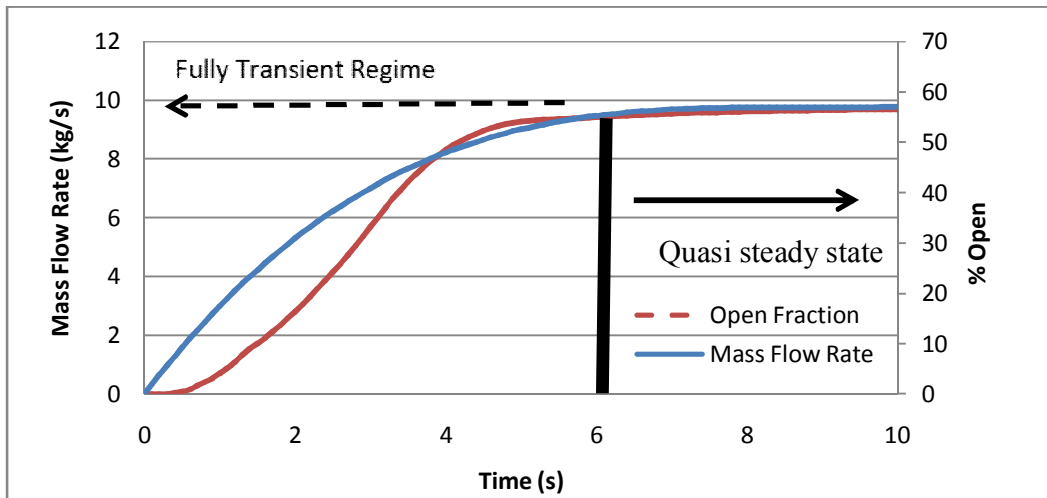


Figure 5.2 Air Mass Flow Rate and Open Fraction

PID controller constants are determined by trial and error method. Vitiator is fired and temperature at station 4 is checked whether simulation condition is supplied or not. Due to the heat loss temperature could be less than required. In this case steps after the 4th, should be repeated with a higher temperature target.

In Figure 5.3, the temperature of station 4 is plotted. Vitiator is fired in the tenth second and temperature rises. In spite of the calculated fuel and air mass flow rate being supplied which is shown in Figure 5.4, the target temperature has not been achieved.

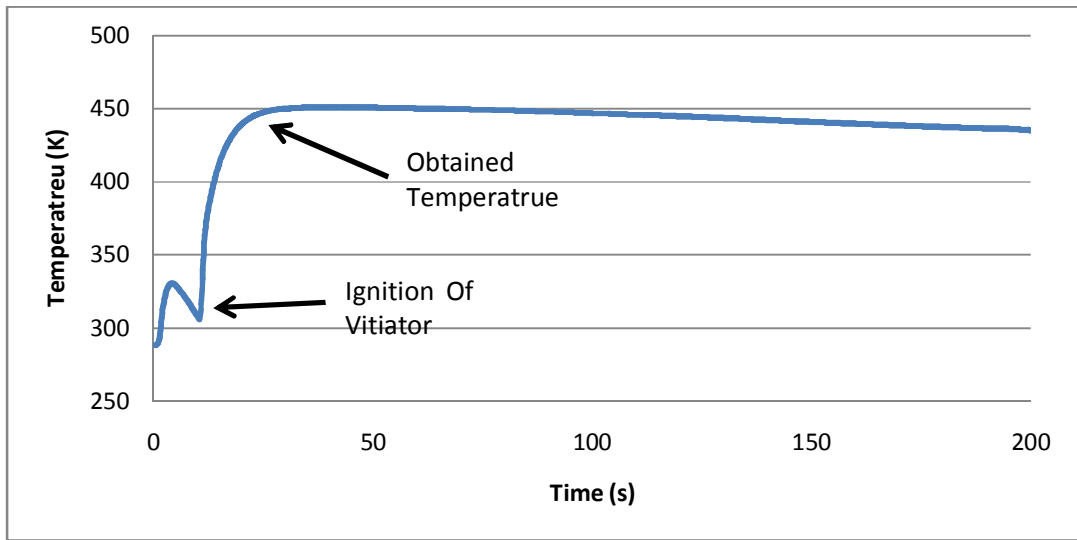


Figure 5.3 Station 4 Temperature Plot

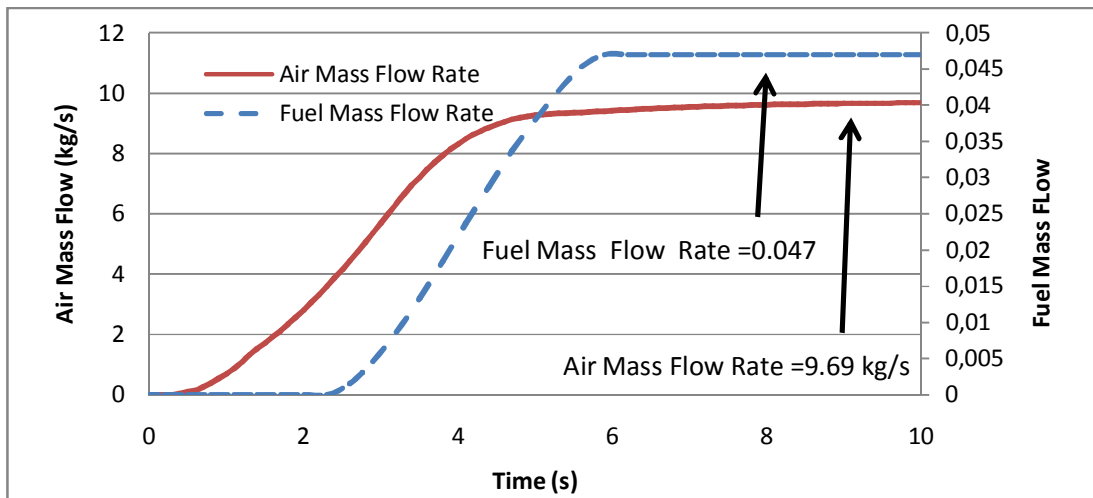


Figure 5.4 Fuel Mass Flow Rate

Not achieving the target temperature, can be explained with the heat losses which are plotted in Figure 5.5.

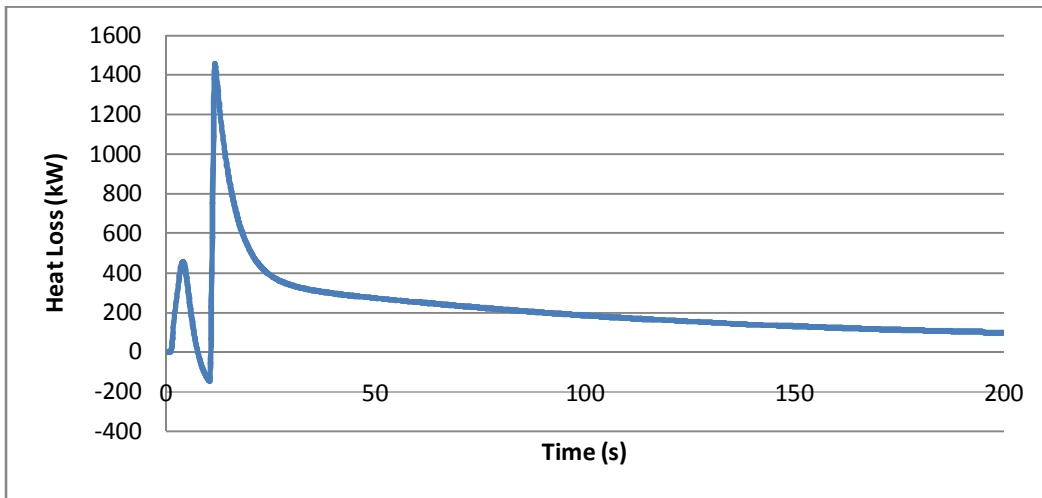


Figure 5.5 Heat Loss from the Interface

Although heat loss is decreasing the temperature of the station 4 decreases. Since vitiator efficiency is not changed in the model inlet condition of the vitiator should be considered for this temperature drop. As shown in Figure 5.6 total temperature of the air storage tanks and inlet condition of the vitiator decreases up to 150 K. Since temperature decreasing is linear and the behavior is known (continuously decreasing), not a PID controller is set to fuel line. During the vitiator execution a linear opening profile is defined.

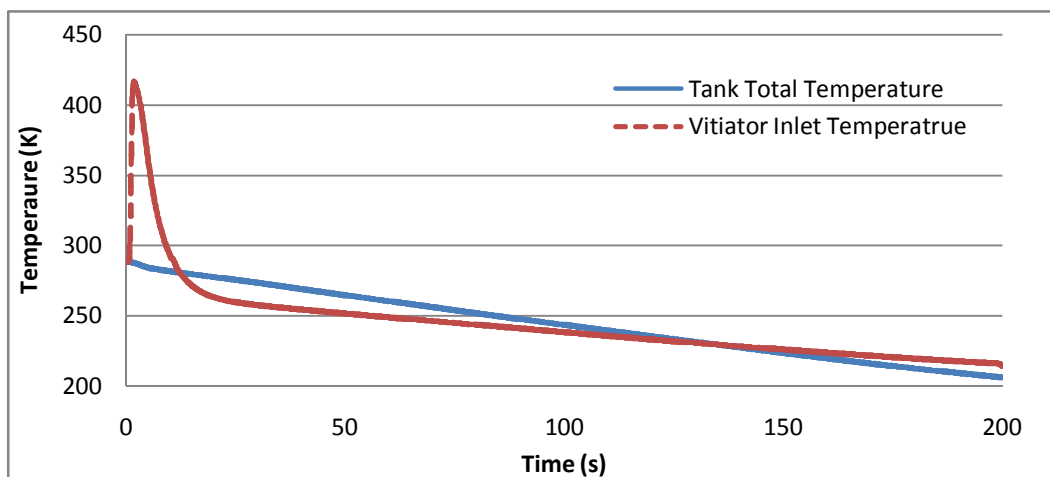


Figure 5.6 Total Temperature

To manage the heat loss problem, according to the flow chart shown in Figure 5.1, 2nd iteration cycle is performed. Iteration data is shown in Table 5-3. In the second temperature cycle new target temperature is determined by adding the difference of “Target Temperature” and “Obtained Temperature”.

Table 5-3 Temperature Iteration Cycles

	1 st iteration	2 nd iteration
Obtained Temperature (K)	450	500
m_{air} (kg/s)	9,69	9,60
m_{fuel} (kg/s)	0,0472	0,0610
m_{oxygen} (kg/s)	0,2631	0,3400
Total Air Msss (kg/s)	10	10

Open Fractions of the control valves are updated according to the new values and the simulation is repeated, as mentioned in the flow chart. Air mass flow rate and the temperature data of the second cycle is plotted in Figure 5.7.

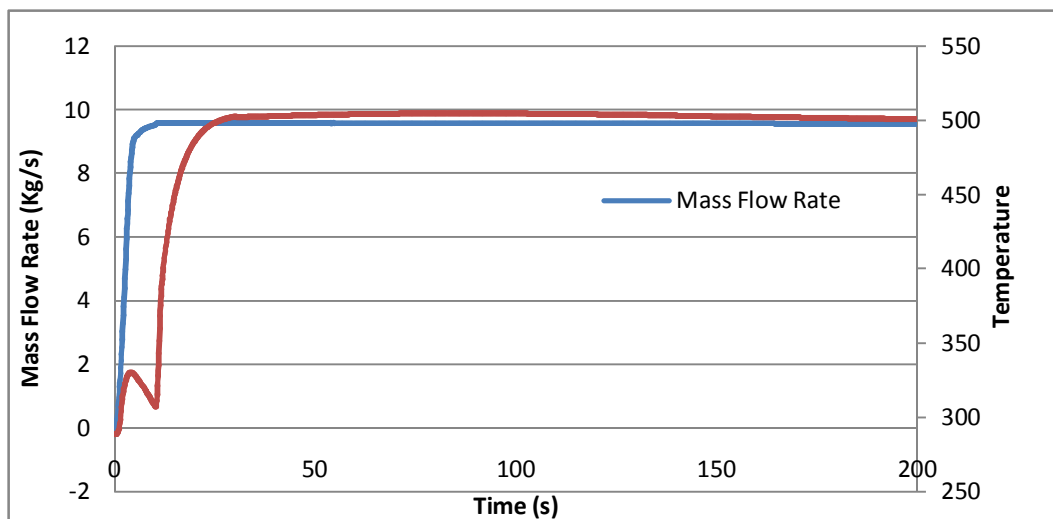


Figure 5.7 Temperature and Mass Flow Rate

Temperature value is obtained as 500K which is lower than required temperature value 518 but iteration is ended at this point. Pressure result of the simulation is plotted in Figure 5.8. Pressure is increased instantly by firing of the vitiator at the 10th second. Pressure converges to 7.3 bar after the t=30 sec thus when temperature and pressure converge to their test values at t=30 sec, ramjet engine is able to fire after t=30s

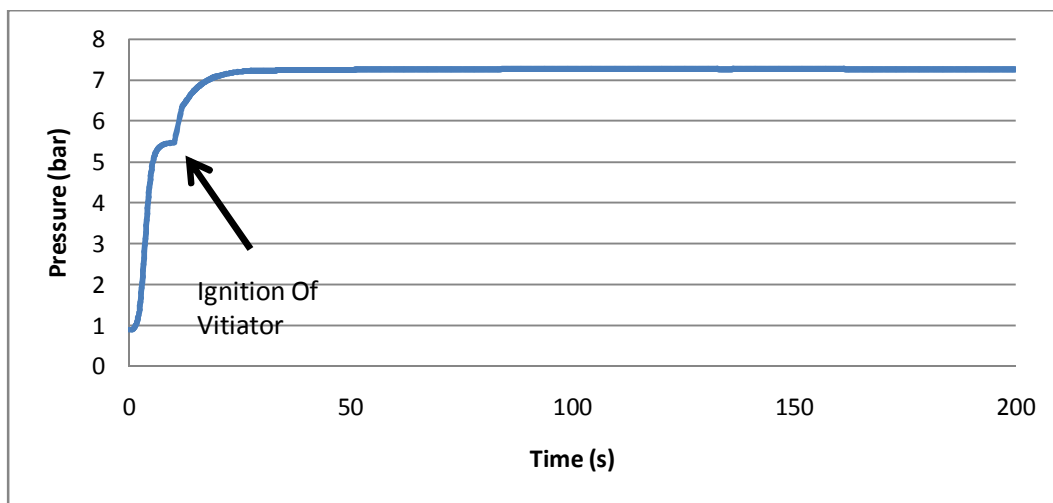


Figure 5.8 Station 4 Pressure Graph

Mass flow rate values of Flownex pipe elements corresponds to station 1, 2 and 3 which are plotted in Figure 5.9.

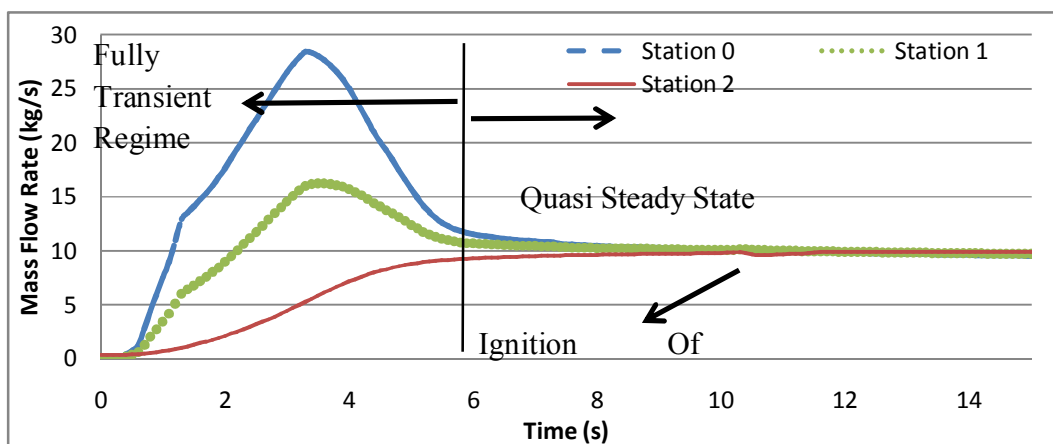


Figure 5.9 Mass Flow Rates on Each Station

At fully transient regime mass flow rate at inlet and outlet of the each station is different but whole system converges at a value without any intervention. Firing of the vitiator is on the 10th second but this event cannot be seen in the flow rate data despite being shown in pressure and temperature data in the stations 3. Reason of this is; second control valve is in chocked condition. Due to the chocked flow, information is isolated from the second control valve. This working condition has a positive effect on the stability by isolating the vitiator and ramjet combustor disturbances.

After this point a ramjet engine is modeled after the interface section and simulation is repeated with the ramjet engine. Assumptions on the ramjet engine are;

- Ramjet fuel mass flow rate is neglected,
- Test conditions are Mach Number 2 and sea level altitude,
- Ramjet engine combustor is modeled as adiabatic heat exchanger.

Tt2, inlet of the combustion chamber is calculated as 518K. To provide Tt4 temperature as 1800K, basically;

$$Q = \frac{10kg}{s} \cdot \frac{1kj}{kgK} \cdot (1800K - 518K) = 13MW$$

Constant heat source is applied to simulate the combustion chamber of the ramjet.

Ramjet engine is ignited in t=30s when test facility is in quasi steady state. Pressure is raised instantly by the ignition of the ramjet as shown in Figure 5.10. Since Mass flow rate is not changed due to the chocked flow on control valve, temperature is not changed.

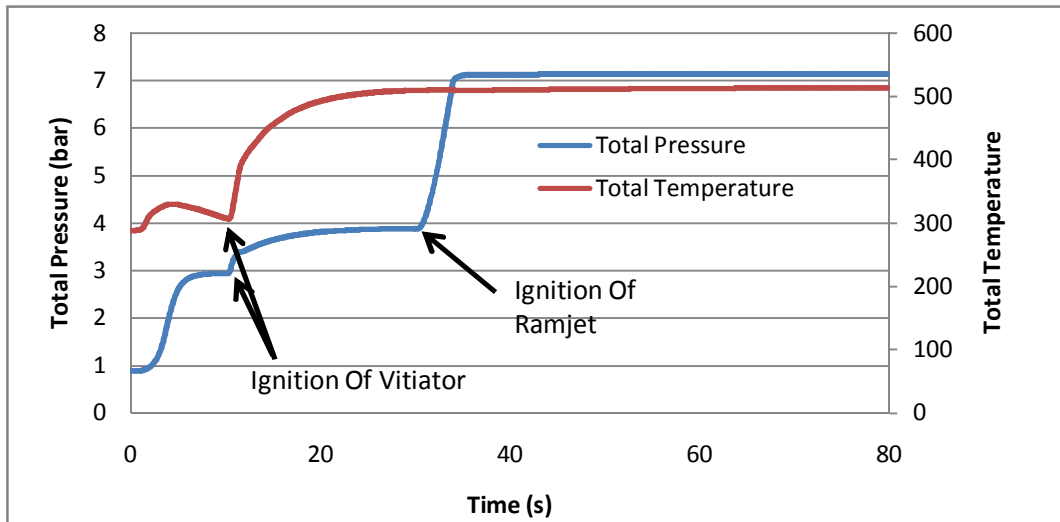


Figure 5.10 Ramjet Test Simulation

CHAPTER 6

CONCLUSION AND RECOMMENDATION

A flight condition is specified for ramjet engine and a conceptual ramjet test facility is designed to perform flight tests. Test facility consists of sub systems such as air storage system, air heater system, test stand and control system. These systems have to work in harmony and with a sequence. To analyze the system response of the test facility, transient numerical model requirement has been emerged.

One dimensional computational fluid dynamic code FLOWNEX is used to perform the numerical model. Numerical model is calibrated with test results and maintained to get accurate results. Measurement equipment such as thermocouples are included in the numerical model, to take into account the response time of the sensors.

To provide the flight condition, test facility has to be controlled simultaneously. The absence of the numerical model, controller and flow parameters such as valve open fractions and open profiles, have to be found only with trial and error tests. This numerical model is used to minimize the test number to configure the flow parameters of the test facility.

In this study, the performance of the air vitiator is taken as constant, thus especially at the transient regimes total temperature value which is directly related with the vitiator performance, has the highest error value. As a future work, by using the test data and detailed CFD solutions vitiator performance may be modeled as a function of pressure and/or equivalence ratio or other effective parameters.

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