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High-speed flight experimental test facilities development in the UAE

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Abstract

High-speed transportation has always been desired by our society to reduce transport time and increase world integration. Unfortunately, since the retirement of Concorde aircraft, we don't have any civilian aircraft capable of it. Supersonic transport for passengers and cargo with a great reduction in flight duration represents a major commercial appeal and holds an empty niche in this market since that. In order to develop economically and physically viable aircraft it is necessary to understand the unique features of compressible flow highlighting it as a field of great interest nowadays. There are several research topics to be investigated in order to develop commercially viable supersonic/hypersonic aircraft and some of them are: The reduction of the sonic boom that could increase the supersonic flight routes; The waverider technology to improve the aerodynamics efficiency; Propulsion systems such as ramjet, scramjet, air turbo rockets to provide the necessary thrust with viable fuel consumption; Subsystems for combined cycles propulsion systems; Materials and GNC systems capable of operating in such harsh environment. As can be seen, plenty of technology development is still necessary in this field and it is impossible to test everything in a single ground test facility. It is then necessary to develop multiple test facilities dedicated to specific subsystems. In this context, experimental facilities capable to provide the desired conditions of high-speed flows in a controlled environment are necessary for testing and verification along all the project stages. There are several types of testing facilities capable of generating supersonic flow, among these the Ludwieg tube has become the chosen one from several institutions around the world due to its versatile characteristics for aerodynamics analysis. To facilitate the development of propulsion systems, there is a need for a specialized test facility capable of replicating the combustion inlet enthalpy for extended durations compared to the current capabilities of the Ludwieg tube. Therefore, we propose the construction of a combustor-level test facility that can effectively evaluate the necessary high enthalpy conditions. In the Middle East, there is a lack of these types of facilities, so we propose a preliminary design based on theoretical and CFD simulation of a Ludwieg tube and a combustor level test facility suitable for R&D. Establishing this capability in the region and thus boosting the national technology and scientific research on this field is our main goal. The objective is to conclude this endeavour with the comprehensive preliminary design of a Ludwieg tube and a combustor test facility, enabling the initiation of the detailed project for deploying these facilities in the near future.

1. Introduction

High-speed flight refers to the ability of an aircraft to achieve velocities that commonly surpass the speed of sound. In contemporary terms, this capability is generally associated with speeds beyond Mach 1. The ability to fly faster than the speed of sound has been an objective of aviation for a very long time. In 1947, Chuck Yeager piloted the Bell X-1, which became the first flight to officially break the sound barrier. Later in 1959 the X-15 (Figure 1) program started with the purpose of investigating high-speed and high-altitude flight regimes of a rocket powered aircraft and during the program's existence performed 199 flights with 12 different pilots [1]. It conducted aerodynamic and thermal research, tested materials, structures, and evaluated flight control systems and technologies. The refinement of aerodynamic models and the development of aircraft capable of sustained high-speed flight were greatly aided by these contributions. The X-15 program was an innovative testbed for the advancement of supersonic and hypersonic flight technologies, yielding valuable data on aerodynamics, materials, flight controls, and human factors. In addition, it provided pilot training and knowledge of the human factors involved in high-speed flight. The success and advancements of the program contributed to the comprehension of supersonic and hypersonic flight and paved the way for future research. Despite the Concorde and TU-177, which were the only commercial airliners to fly at supersonic velocities, a few high-speed aircraft have been developed recently, but they have been primarily for military use [2].

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Figure 1: X-15 Smithsonian [3].

The development of a supersonic flight vehicle is a complex undertaking, and several challenges must be overcome to achieve it. Despite previous advancements in the development of similar aircraft in the past, numerous aspects require further comprehension and clarification to ensure the technological and economic viability of these aircraft. Some of these challenges encompass features related to the nature of supersonic flows, such as the increased drag with speed and reduced lift, the generation and interaction of shock waves with the airframe, as well as the occurrence of viscous aerodynamic heating. The aircraft's airframe must be developed to withstand the extreme forces and temperatures generated by supersonic flight. At subsonic speed, the aircraft uses the atmosphere as a heat sink since at higher altitudes the temperature is low, while at supersonic speed the surrounding flow is hotter than the aircraft, requiring a complex heat management system [4]. The development and operation of such flights are costly, making it difficult for some applications to adopt them, so the cost must be considered from the conceptual stages of the project.

Despite the obstacles, the development of aircraft capable of high-speed flight has numerous potential advantages, including a reduction in travel time between two locations, which can benefit both business and leisure travel as well as cargo transportation. With the advent of faster aircraft, it is possible to increase the latency of transporting cargo and passengers, as the transit time will be reduced; this can help reduce congestion and increase efficiency. Such benefits can create new opportunities for commerce, tourism, and economic development [5]. Therefore, even though the development of such vehicles is a complex and difficult endeavour, the potential benefits are substantial and justify the effort, as a country can anticipate an economic lift from such investments. Employment creation, increased tourism, and congestion reduction are some of the economic benefits of faster transportation. Providing a faster and more dependable method of transporting soldiers and equipment, it can also contribute to the improvement of national security. Another aspect of technological development is the increase of a nation's prestige by demonstrating its technological prowess and dedication to innovation.

1.1 UAE economy diversification

The United Arab Emirates (UAE) has been actively pursuing a strategy of economic diversification aimed at reducing its reliance on oil and fostering the growth of a more sustainable and multifaceted economy. This includes developing non-oil sectors such as finance, logistics, manufacturing, renewable energy, technology, and healthcare, as well as developing its tourism and hospitality industry (Figure 2). It has also established itself as a regional hub for financial and business services and created free zones and special economic zones to attract foreign investment and promote specific industries. The UAE has made significant investments in innovation and technology, manufacturing and industrial development, and renewable energy projects. These efforts have been driven by strategic planning, infrastructure investments, policy reforms, and an emphasis on innovation and entrepreneurship [6].

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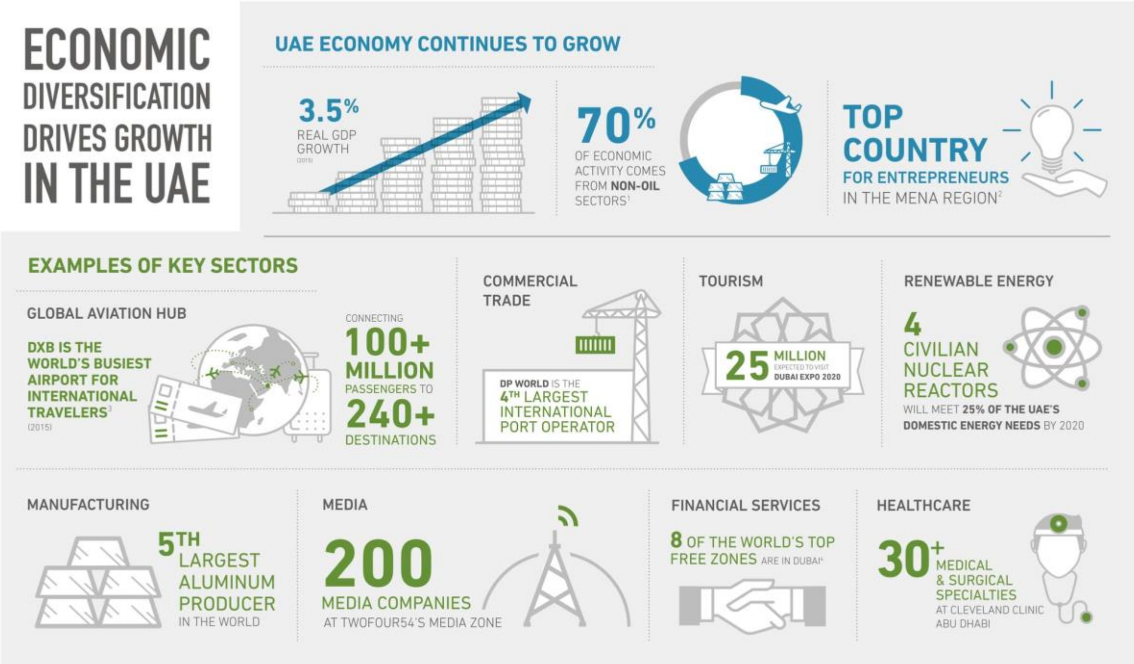

Figure 2: UAE economy diversification [7].

The Country has allocated significant funds in education and research to create a competent labour force and a thriving research community, establishing world-class universities and research institutes and funding research initiatives in a variety of disciplines, such as renewable energy, healthcare, artificial intelligence, and aerospace. The UAE has created several policies and initiatives to promote innovation, these initiatives seek to foster an environment conducive to innovation by providing funding, assistance, and market access. Significant progress has been made in its transition to a knowledge-based economy, and the country is becoming a regional innovation centre due to the rapid expansion of its industries [8]. It is currently ranked among the top 20 countries for innovation, and it is well-positioned to continue its economic development in the coming years. The development of research and development at high speed fulfil the plans to diversify the Country's economy since investments in aerospace research can lead to technological advancements, national security, economic growth, job creation, global competitiveness, scientific and engineering excellence, spin-off benefits, and long-term societal and economic benefits.

1.2 Experimental facilities necessity

The utilization of experimental facilities is imperative for conducting research on high-speed aircraft due to various reasons. Despite the notable advancements in numerical tools, experimental facilities continue to hold significance since these facilities serve as a mechanism for validating and verifying the precision of numerical tools and simulation models. The R&D developments go through intricate aerodynamic phenomena such as flow separation, boundary layers, shock waves, and their interactions. Accurately capturing these phenomena through numerical simulations can pose a challenge due to the inherent complexities and uncertainties involved. Experimental facilities offer a means to directly observe and quantify these phenomena, facilitating the researcher's acquisition of a more profound comprehension and enhancing computational models accordingly [9].

Experimental facilities provide the opportunity to investigate and explore factors or phenomena that may not be accounted for in current numerical models and can be anticipated before the flight tests. The provision of flexibility enables researchers to make necessary adaptations and modifications to their experiments, thereby facilitating the exploration of novel possibilities and the discovery of unforeseen outcomes. The aforementioned discoveries through experimental testing, together with the integration of numerical simulation, give a comprehensive approach with a significant potential to propel additional progress in the realm of high-velocity aircraft engineering.

Preliminary dimensional analysis and similarity are essential for experimental testing, providing a systematic and efficient approach to understanding, analysing, and interpreting experimental (scaled model) and real (full-scale) data.

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They help establish a consistent framework for conducting experiments and reporting results, providing insights into scaling relationships between variables in a physical system. Model testing is also important, as it preserves relevant dimensionless numbers between the model and the full-scale system to ensure that the behaviour observed accurately represents the larger system. These concepts help researchers make efficient use of resources, gain valuable insights, and advance scientific knowledge and engineering practices. The combination of experimental and computational approaches offers a comprehensive understanding of aircraft performance, safety, and operational requirements. In order to develop experimental test facilities for a supersonic flight we need to evaluate the flight parameters to be tested. Figure 3 shows an example of the Mach number and Reynolds of some aerospace vehicles according to their flight corridor [10].

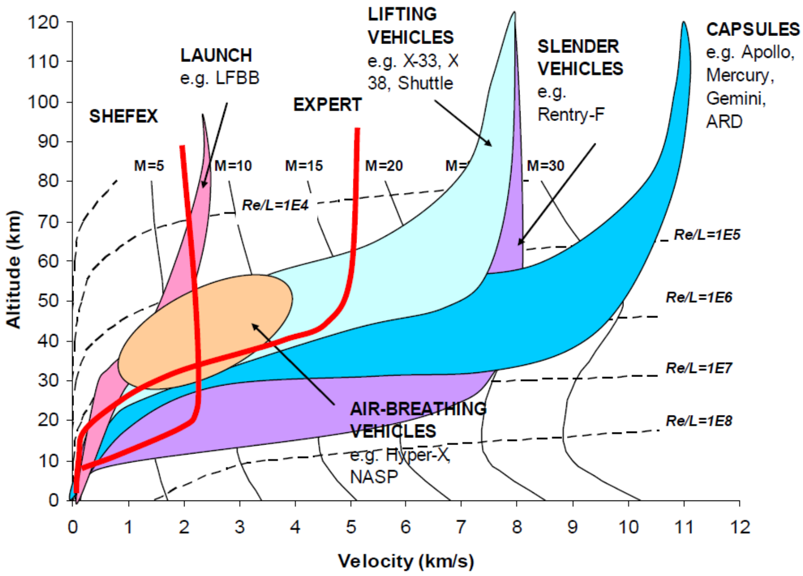

Figure 3: Flight regimes of interest [10].

Hornung published a good approach to subscale simulation of hypersonic aerodynamic flow fields in 1988 [11]. For a blunt body with air flows at sea level, the lowest speed at which chemical reactions have a significant role is around 2 km/s. This is roughly equivalent to a stagnation temperature of 2000 K. Figure 4, shows that the perfect gas model holds for air at speeds below 2 km/s because the isentropic exponent, either remains constant or only changes with temperature as a result of vibrational excitation. Any dimensionless quantity in this situation will depend on the flow's dimensionless parameters. This means that duplication of a combination of dimensionless flow parameter guarantees that the dimensionless quantity being studied in a subscale model in a wind tunnel will also be replicated.

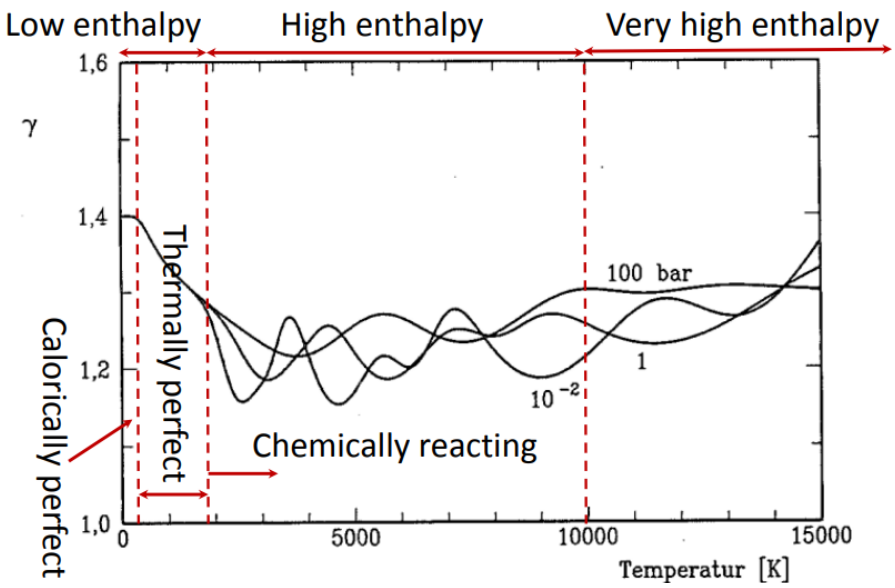

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Figure 4: Variation of the isentropic exponent, γ, of air with temperature and pressure [12].

Wind tunnel testing offers several advantages over flight testing in the development and evaluation of aerospace vehicles. These include a controlled environment, safety, cost-efficiency, early design evaluation, and refinement of design concepts before the costly and time-consuming process of flight testing. The controlled and repeatable environment for conducting experiments allows for systematic and accurate data collection. It also offers a safer alternative to flight testing without the inherent risks associated with actual flight. Wind tunnel testing provides the opportunity to identify design flaws, make necessary modifications, and optimize performance before moving to flight testing, reducing the risk of expensive design iterations. However, flight testing remains essential for validating and verifying the performance of aerospace systems in real-world conditions. The two testing methods are often used in conjunction to gather comprehensive data and ensure the accuracy of predictions made in wind tunnel environments.

2. Experimental test facilities

Even though a flight test seems to be a more direct and comprehensive approach to verifying a complete flying system at once, it is often quite expensive and carries a not negligible component of danger. It is then common practice to split the problem into different aspects and test them in an isolated fashion. This approach allows to develop specific and optimized designs for the facilities dedicated to the investigation of these aspects, and at the same time, it is still able to provide a good overview of the entire problem. There are several types of experimental test facilities dedicated to testing supersonic aircraft and they are focused on different phenomena such as aerodynamics, propulsion, structural, and materials development. Increasing the speed to be simulated also increases the complexity of the test facility since it should be able to sustain the same flow properties and conditions that the model would encounter during real flight [13].

There are different types of wind tunnels to test and study the aerodynamics of supersonic aircraft. Among them, we have the Blowdown Wind Tunnel (BWT), and Pulsed Wind Tunnel (PWT).
A BWT uses compressed air to generate high-speed airflow to simulate the conditions experienced by the aircraft in flight. The compressed air is stored in a storage tank and directed through a convergent-divergent nozzle to accelerate the airflow to supersonic speeds through the test model. The flow deceleration is achieved using diffusers and expansion chambers. BWTs are limited in their testing time and require replenishment of the compressed air supply after each test run.
A PWT uses intermittent bursts of high-pressure air to simulate the conditions experienced by the aircraft in flight. The compressed air is stored in a reservoir and released in short-duration pulses through a fast-acting valve. The test time is in the order of milliseconds due to limitations on reservoir sizing.

When it comes to testing supersonic aircraft propulsion systems, there are specialized facilities such as the Direct Connected Test Facility (DCTF). It consists of a test stand, instrumentation, data acquisition systems, and control systems that allow researchers to regulate and control the operating conditions of the engine during the test. The test stand provides structural support and ensures a safe connection between the engine and the test equipment. DCTFs are used to simulate flight scenarios and study the engine's response. They have an exhaust system, thrust measurement system, performance analysis, test execution and evaluation, and direct connected test facilities. These facilities enable detailed analysis and provide valuable insights into the behaviour and characteristics of the propulsion system under realistic operating conditions.

2.1 Flight corridor analysis

The flight corridor for supersonic airbreathing engines is the range of altitudes and speeds at which engines can operate efficiently. It is limited by factors like oxygen availability, heat and mechanical load which depends on altitude and flight speed. High altitudes have less oxygen, leading to engine flameout while low altitudes have more air density, causing increased drag and heat loads which may lead to aircraft damage. The typical flight corridor varies the altitude by Mach Number, allowing engines to operate safely and efficiently (Figure 5). To prevent overheating, high-speed aircraft must be designed to withstand high temperatures and be cooled. Cooling methods include passive cooling by structure design or active cooling which uses the fuel to absorb the heat and keep the engine cooler.

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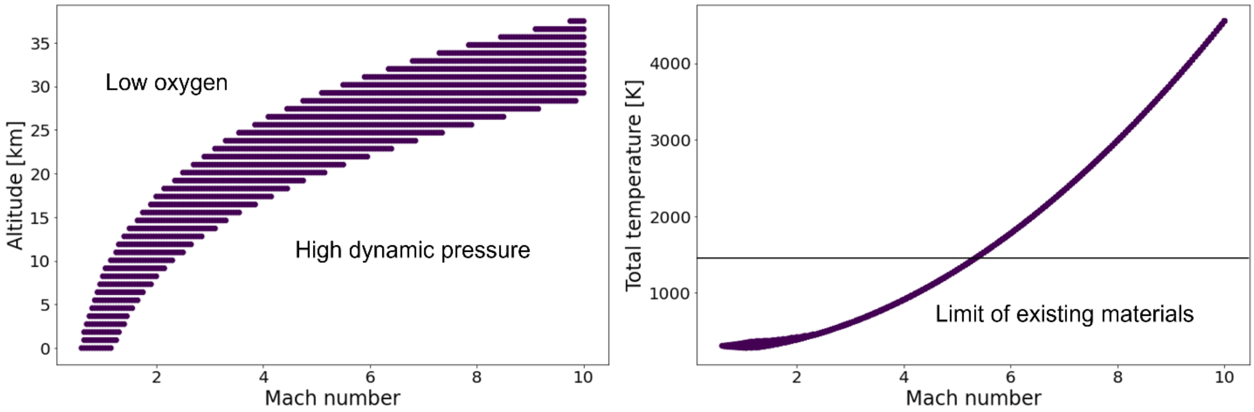

Figure 5: Flight corridor analysis for an airbreathing vehicle.

For flights above Mach 5, we are in a high enthalpy area in which the air has different behaviour and requires specific test facilities. Depending on the vehicle's surface temperature there is no existing material capable of withstanding the heat directly for a long period of time. In general, materials that are used in supersonic aircraft must be able to withstand temperatures of up to 500°C. Some materials, such as titanium and carbon composites, can withstand temperatures of up to 1000°C, but this is practically the existing limit. The surface heating of supersonic and hypersonic vehicles caused by air friction is extreme and represents one of the most challenging aspects in the development of this technology as it increases with velocity. To avoid and withstand this limitation it was proposed vehicles flying up to a maximum velocity of Mach 5 and within the dynamic pressure corridor.

Figure 6 presents the required dimensional parameters that must be simulated in the experimental test facilities to guarantee the similarity between the experimental and real flight, in this case we are considering Mach Number and Reynolds number for aerodynamics analysis and total temperature for combustion analysis. The parameters change based on the flight Mach number and altitude, so to evaluate the entire envelope of operation different test facilities might be required. Another important parameter that must be matched in the experiments is the ratio $^{T_w}/_{T_o}$ to guarantee the proper boundary layer development [14]. Depending on the simulated conditions a heated model might be required to maintain the same ratio since, it has been shown that the wall temperature ratio strongly influences the size of separation bubbles, and it strongly influences the transition behaviour of boundary layers [15].

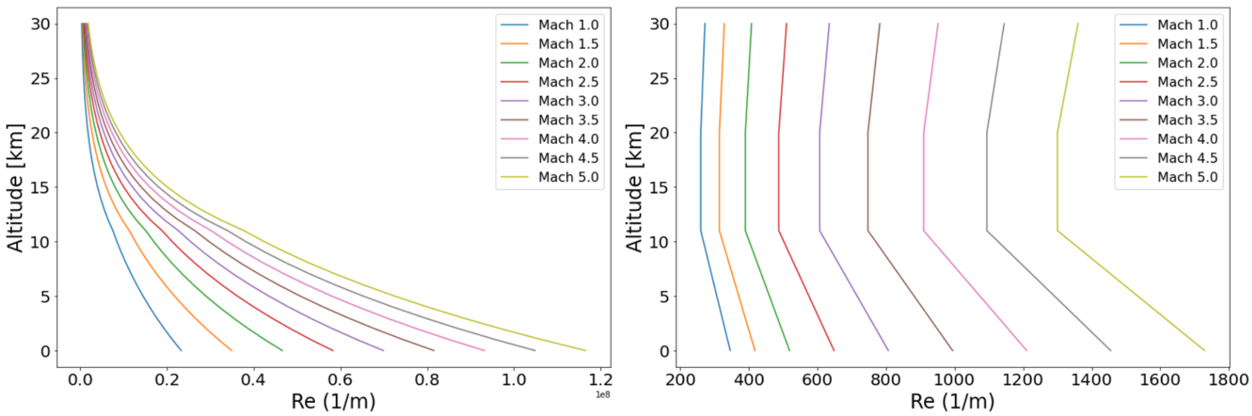

Figure 6: Dimensional analysis for the proposed flight corridor.

2.2 Facilities planned to be developed at TII

Considering the technical challenges and existing available technology it has been proposed to develop test facilities to investigate flights up to 30 km of altitude and Mach number between 3 and 5. Based on these requirements it has proposed the development of a Ludwieg tube, a combustor-level test facility, and a blow-down supersonic wind tunnel. Combining these 3 different facilities it is possible to perform most of the required tests in the development of a high-speed aircraft from an aerodynamics and propulsion perspective. The Ludwieg Tube is an affordable test facility for

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aerodynamics analysis, and despite its test duration, it is a versatile facility. The directed connected test facility must match the total temperature that the vehicle will face during the flight and the conditions inside the vehicle combustion chamber. With such a facility it is possible to develop the required propulsion system as well as execute material experimental testing. The blown down wind tunnel offers a longer test time than the Ludwieg Tube which may allow testing of transient phenomena such as moving surfaces but comes with a higher cost.

2.2.1 Ludwieg tube at TII

The Ludwieg tube is a tool used for studying high-speed gas dynamics or supersonic/hypersonic aerodynamics. Its concept was developed in the 1930s by Heinrich W. Ludwieg, with Adolf Busemann as his collaborator. A standard Ludwieg tube layout consists of a high-pressure gas reservoir, called driver, followed by a test-run trigger component, a nozzle, a test section, a diffuser and a dump tank (Figure 7). The stagnated gas is maintained inside the driver tube by a physical barrier upstream of the nozzle entrance which can be a diaphragm or a fast action valve. When this barrier is suddenly removed it triggers the flow generation into the test section [16].

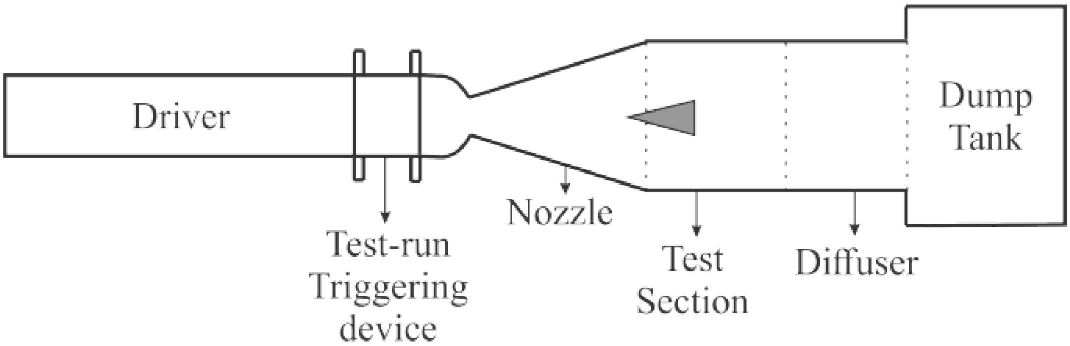

Figure 7: Ludwieg tube simplified layout [17].

The proposed Ludwieg tube aims to cover a Mach number range between 3 and 5, simulating flight conditions at related altitudes as per the flight corridor concept explained in section 2.1. This choice is primarily driven by the technical restraints for material development. Simulating flight up to Mach number 5, the tube can replicate the necessary stagnation pressure requirements within a laboratory setting. Additionally, achieving the desired flow quality becomes feasible without requiring a large driver tube diameter. To facilitate applied research, a test chamber with a cross-section size of 500 mm is considered highly suitable. In terms of test duration, a desired time of 100 ms is set. This timeframe allows for a wider variety of data acquisition techniques and enables a larger quantity of measurements for each test run. By extending the test time, researchers can gather more comprehensive data during experiments.

According to [17], in order to ensure good quality flow, it is recommended to set the driver Mach number at M 0.045. Based on existing Ludwieg tube facilities the stagnation temperature is expected to be as high as T0 = 750 K using electric heating. The analysis of the flight corridor allows us to determine the requirements for stagnation conditions, with a maximum pressure (P0) of approximately 3 MPa needed to replicate real flight conditions. To ensure safe operation and expand the achievable Unit Reynolds envelope, a safety factor of 2.67 was introduced, extending the maximum allowable pressure of the facility to 8 MPa. By analyzing the capabilities of existent facilities, the estimated range for the Unit Reynolds envelope is expected to be between $Re = 5 \cdot 10^6\ m^{-1}$ and$50 \cdot 10^6\ m^{-1}$. Finally, Table 1 provides a compilation of the initial key parameters for the proposed facility.

M	**3 to 5**
Nozzle exit diameter	500 mm
Test time	100 ms
$\boldsymbol{P_o}$ **max**	8 Mpa
$\boldsymbol{T_o}$ **max**	750 K

Table 1: Ludwieg tube operation parameters.

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With such a facility it will be possible to develop research in aerodynamics for the development of aerodynamics characterization required. Even though the test time is short, experiments can be performed at a low cost and can be used for the preliminary design and first required validations.

2.2.2 Direct Connected Test Facility

A Direct Connected Test Facility (DCTF) is a valuable tool for combustor analysis, as it simulates flow conditions inside a combustor, allowing researchers to study the combustion process in a controlled environment and identify potential problems. Also, since the flow reproduced in this facility must match the maximum temperature inside the combustion chamber, it can be used to perform materials studies. DCTFs are used to study flame stability, emissions and combustion performance which contribute to ensuring the vehicle propulsion performance and keeping the required environmental regulation. Such facilities can be used to study various combustor types, including gas turbines combustor, ramjet combustors, scramjet combustors, and air-turbo-rockets with different types of fuel that can vary according to necessity. The analysis of combustors in a controlled environment generates high-quality data and allows the study at various scales, from small laboratory-scale to large full-scale combustors. Since the facility is dedicated to the combustor it is possible to isolate and study the effects of individual parameters on combustor performance and improve it. Overall, DCTFs are a valuable tool for combustor analysis, enabling researchers to improve combustor performance and reduce emissions.

A DCTF consists basically of a pressurized dry air supply system to simulate airbreathing engines at different altitudes, a heater to simulate the total temperature inside the combustor and the required subsystem to control the pressure and temperature to the desired test conditions. For the heater, there are three main options available, which are the electrical heating, the air vitiator and the pebble bed heater. An electrical heater consists of elements that generate heat when an electric current passes through them. It offers a continuous and controllable source of heat, allowing for accurate temperature regulation during the experiments. An air vitiator heats the air through chemical reactions. Fuel is added to the dry air and combustion takes place increasing the flow temperature up to the desired value. Since part of the oxygen is consumed in the combustion and products from the combustion remain in the flow (air vitiation) the oxygen content needs to be adjusted to match the atmospheric reference value. The pebble bed heater uses high-temperature ceramic pebbles capable of retaining heat. These pebbles are preheated using an external source, then they release the accumulated heat to the airflow during the test.

For combustions analysis, since the air vitiator changes the air properties and the pebble bed offers low control over temperature, it has been proposed the implementation of a solution based on an electrical heater. The electrical heater offers good controllability of temperature and versatility but requires a large investment in the equipment and infrastructure for the required electrical power supply. The proposed DCTF basic layout utilizes an inline electrical heater from TUTCO and a dry air supply from pressurized tanks. Based on a preliminary analysis of heat requirements and power availability a heater of 3.4 MW has been proposed. Figure 8 shows a sketch of the proposed DCTF basic layout together with the heater capability depending on mass flux and temperature increment.

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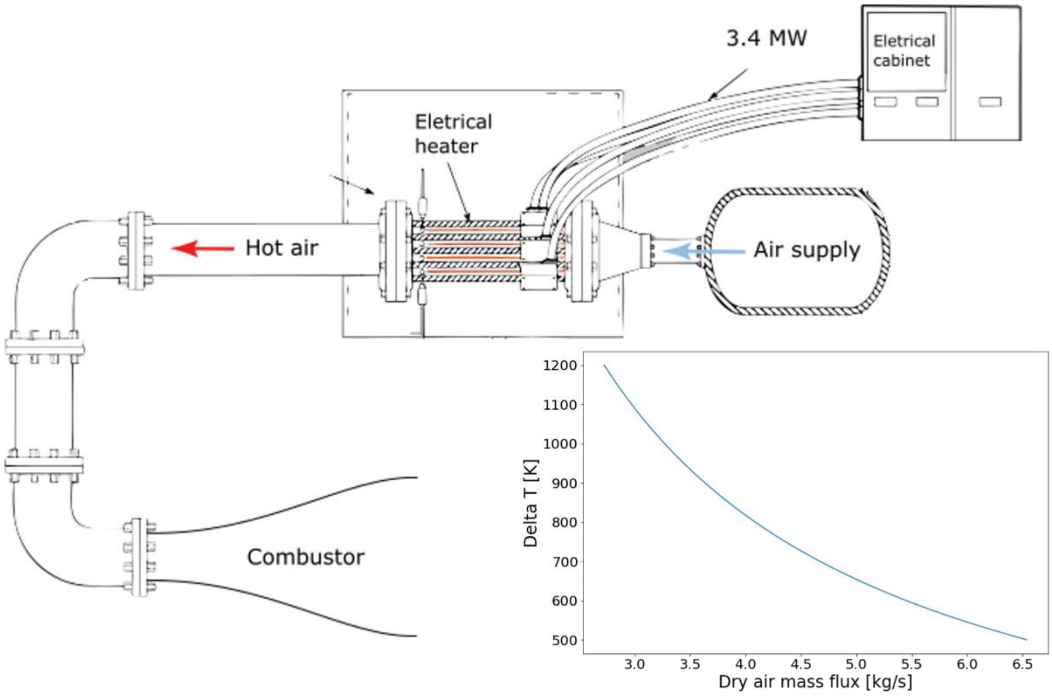

Figure 8: Adapted from TUTCO [18].

2.2.3 Blowdown supersonic tunnel

A blowdown supersonic wind tunnel (BWT) offers a longer test time when compared to the Ludwieg tube. This time is in the order of seconds, allowing the analysis and validation of transient phenomena. The test gas in this type of tunnel is pressurized by a compressor in the reservoir. When released, the gas expands through a nozzle, creating a supersonic flow in the test section, and eventually expanding into a vacuum chamber. These tunnels are commonly used in research related to supersonic aerodynamics, as well as testing new materials and coatings. The extended test time provided by blown-down supersonic wind tunnels necessitates the use of large pressure vessels and vacuum chambers. The design of a blown-down supersonic wind tunnel is intricate and requires careful consideration of various factors such as the size and shape of the test section, the length of the test section, the type of nozzle, the pressure of the gas reservoir, the flow rate of the gas, and the method of flow control. Testing the wind tunnel is crucial to ensure it meets the desired flow conditions, and once the testing phase is completed successfully, the tunnel is ready for operational use. Blowdown supersonic wind tunnels serve as valuable tools for research in the field of supersonic aerodynamics and the testing of new aircraft and missiles.

Pope (1965) presents a roadmap outlining the development of blowdown wind tunnels and identifies the key parameters that should guide the preliminary sizing process. The primary considerations in tunnel sizing, which directly impact the cost, are the dimensions of the test section and the desired test time. The test section must be adequately sized to accommodate models that maintain flow similarities at scaled level, while the test time must be sufficient for accurate measurements of relevant phenomena. To enable transient tests, a blowdown wind tunnel with a nozzle exit diameter of 1.2 meters and a test time lasting a few seconds has been proposed. However, constructing a facility with such capabilities involves substantial requirements in terms of space, power, and budget. Further investigation is necessary to identify potential suppliers and partners who possess the expertise and resources to meet these specific requirements.

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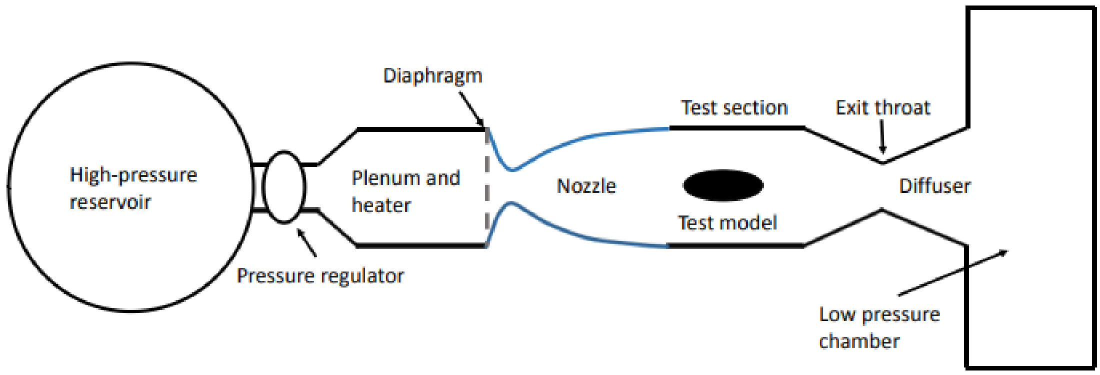

Figure 9: Blown down wind tunnel basic layout [12].

3. Conclusion and Remarks

Investing in supersonic experimental facilities is a complex decision that requires a comprehensive analysis of a country's strategic, economic, and technological priorities. Key factors to consider include technological advancements, national defence and security, economic opportunities, environmental considerations, international collaboration and competition, cost and resource allocation, and international collaboration and competition. Technological advancement in aerospace and high-speed flight have the potential to foster innovation, enhance aircraft performance, and potentially introduce transformative technologies in various sectors. National defence and security can benefit from supersonic capabilities, while economic opportunities can arise from the development of commercial aircraft and growth in related industries. Environmental considerations, such as noise pollution and fuel efficiency, can be addressed through research into quieter and more fuel-efficient supersonic technologies.

Investing in supersonic facilities can facilitate international collaboration and competition, enabling the exchange of knowledge and potentially influencing international standards and regulations. Ultimately, the decision to invest in supersonic experimental facilities requires a thorough analysis of a country's strategic, economic, and technological priorities. This analysis should consider the potential benefits, feasibility, and weigh them against other national priorities and available resources.

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