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A route to learning supersonic aerodynamics in atmospheric flights for engineering students based on a revision of Bloom's taxonomy

Una ruta para aprender aerodinámica supersónica en vuelos atmosféricos para estudiantes de ingeniería basada en una revisión de la taxonomía de Bloom

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Abstract

According to Deloitte, the global aerospace industry in 2018 experienced a solid year with the demand of passengers and the strengthening of global military spending that continues to increase. Furthermore, it is expected to continue its growth trajectory in 2019 and the following years, led by the growing production of commercial aircraft and strong defense spending. The growth of aircraft production requires the designs to be supported by the knowledge and experience of qualified personnel. In the case of aerodynamic performance, it is evaluated according to the speed range considering incompressible or compressible flow for subsonic and supersonic speeds, respectively. Based on a revision of Bloom´s taxonomy this article proposes a route to learning supersonic aerodynamics for engineering students, considering and discussing the basic literature and technology used in this area of knowledge. The present work is divided into seven parts, beginning with the introduction which includes the main Fundamental concepts of the supersonic systems. The second part deals with Supersonic Aerodynamics Theory, relevant in this learning route; subsequently, the third and fourth part display a brief description of the Experimental supersonic aerodynamics and Computational Fluid Dynamics - CFD is made. Finally, is approached the Bloom´s taxonomy and a revision and is proposed a route to learn supersonic aerodynamics designed for engineering students.

Key words: supersonic aerodynamics, route to learn, aerospace industry, bloom's taxonomy, learning objectives.

Resumen

Según Deloitte, la industria aeroespacial mundial en 2018 experimentó un año sólido con la demanda de pasajeros y el fortalecimiento del gasto militar mundial, que continúa aumentando. A su vez, se espera que continúe su trayectoria de crecimiento en 2019 y los años siguientes, liderado por la creciente producción de aviones comerciales y un fuerte gasto en defensa. El crecimiento de la producción de aeronaves requiere que los diseños estén respaldados por el conocimiento y la experiencia de personal calificado. En el caso del rendimiento aerodinámico, se evalúa a partir del rango de velocidad considerando flujo incompresible o compresible para velocidades subsónicas y supersónicas, respectivamente. Con base en una revisión de la taxonomía de Bloom, se propone una

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ruta para aprender aerodinámica supersónica para estudiantes de ingeniería, considerando y discutiendo la literatura básica y la tecnología utilizada en esta área del conocimiento. El presente trabajo se divide en siete partes, comenzando con la introducción que incluye los principales conceptos fundamentales de los sistemas supersónicos. La segunda parte trata de la teoría de la aerodinámica supersónica, relevante en esta ruta de aprendizaje; ya en la tercera y cuarta parte, se realiza una breve descripción de la aerodinámica supersónica experimental y la dinámica de fluidos computacional – CFD. Finalmente, se aborda la taxonomía de Bloom y una revisión y se propone una ruta para aprender aerodinámica supersónica diseñada para estudiantes de ingeniería.
Palabras clave: Aerodinámica supersónica, Industria aeroespacial, Ruta de aprendizaje, Taxonomia de Bloom, Objectivos de aprendizaje.

1. Introduction

The Supersonic systems are designed for different purposes (Supersonic Commercial Transport, Space Science, Space Exploration, Planetary Exploration, Manned Spaceflight, Technology Verification, and Military Applications, among others). To design supersonic systems, it is necessary to analyze and determine the aerothermodynamics environment and the associated phenomena that the aircraft will experience due to the interaction with the surrounding in diverse flight conditions and during all operational scenarios.

According to Deloitte, the global aerospace industry in 2018 experienced a solid year with the passenger´s demand and the strengthening of global military spending that continues to increase. Furthermore, it is expected to continue its growth trajectory in 2019 and following years, led by the growing production of commercial aircraft and the strong defense spending (Lineberger, 2019).

The growth of the aerospace industry requires the designs to be supported by the knowledge and experience of qualified personnel. In the case of aerodynamic performance, it is evaluated according to the speed range considering incompressible or compressible flow for subsonic and supersonic speeds, respectively. In this work, a route to learning supersonic aerodynamics for engineering students is proposed, considering and discussing the basic literature and technology used in this area of knowledge.

Engineering students in a supersonic aerodynamics course must know initially, some fundamental concepts in thermodynamics, fluid mechanics (compressible and non-compressible flow), aerodynamics and atmospheric flight. In the supersonic field, three main areas must be considered: Supersonic Aerodynamics theory, Experimental Supersonic Aerodynamics, and Computational Fluid Dynamics – CFD. Finally, the concept of hypersonic aerodynamics is approached, because aerospace systems generally trend to reach high speeds.

1.1 . Fundamental concepts

At first, it is necessary to consider some fundamental concepts that are common in the engineering programs, like the thermodynamic concepts. A brief review of thermodynamic, particularly entropy, isentropic flow, and thermodynamic laws is appropriate consider a perfect gas where the intermolecular force is neglected, the state equation generally is expressed as follow (eq. 1). (Anderson, 2011)

$$p = \rho RT \qquad (1)$$

Where p, ρ, R, T are the pressure, density, specific constant of the ideal gas and temperature, respectively. This equation is expressed in more ways depending on the variables considered. Based on the first chapter of the “Modern Compressible Flow: With historical perspective” (Anderson, 2003). It is necessary to remember the energy and enthalpy concepts to obtain the specific heat relation (eq. 2).

$$\gamma = \frac{C_p}{C_v} \qquad (2)$$

Where C_p, C_v, and γ are the specific heat at constant pressure, specific heat at constant volume and the relation between them, respectively. The relation γ, for a perfect air in standard conditions is $\gamma = 1.4$.

On the other hand, for understanding the flow behavior interacting with a body or in movement, it is necessary to consider some fundamental laws of nature that can be applied in the mechanical flow (fluid flows) like Navier-Stokes (NASA, 2015). Equations that describe how the velocity, pressure, temperature, and density of a moving fluid are related. To know that, it is necessary to analyze a finite control volume and an elemental fluid element, both with fluid moving through it and moving along a streamline with the fluid. Considering additionally, molecular motion of particles and the kinetic energy theory is possible and necessary to approach the physical principles of Continuity (Mass can be neither created nor destroyed), Momentum (The time rate of change of momentum of a body equals the net force exerted on it) and Energy Equation (Energy can be neither created nor destroyed; it can only change in form). (Anderson, 2015). This analysis can be applied to compressible fluids, which is the object of study in the supersonic field.

1.2 . Compressible flow

According to Anderson, the Compressible flow is commonly defined as variable-density flow; in contrast to the incompressible flow (for gas velocities less than about Mach number 0.3), where the density is assumed to be constant throughout. In real life any flowing fluid is incompressible. However, with some gases under certain conditions, the density changes are so small that the assumption of constant density can be made with reasonable accuracy. Physically, the compressibility is the fractional change in volume of the fluid element per unit change in pressure. When a gas is compressed if no heat is added to or taken, is adiabatic, and if the compression is reversible, then it is isentropic. (Anderson, 2003)

To analyze a compressible fluid, the phenomenon must occur within the atmosphere and thus the concepts of atmospheric flight are necessary.

1.3 . Atmospheric flight

In an atmospheric flight four Aerodynamic forces act in a vehicle as follows: Thrust (T), Drag (D), Lift (L), and Weight (W) (Anderson, 2003). Also, it is necessary to have into account the Reynolds number (Re) and Knudsen number (Kn). (Anderson, 2011). As well, according to the U.S Standard Atmosphere 1976, in the atmosphere the most relevant properties are pressure (P), temperature (T), Density (ρ), Viscosity (μ), and Dynamic Pressure (q_0). The atmosphere properties change according to the altitude with different temperature, density, pressure, among other variables. However, there are two general methods to analyze it: based on the Medium Sea Level (MSL) or based on gravity and the centre of the Earth, named geometry and geopotential altitude, respectively. (U.S. Standard Atmosphere, 1976).

It is necessary to remember that the fluid is considered compressible or incompressible according to the speed. For supersonic speeds, the velocity is measured in Mach number that depends on the speed of sound and this of the temperature of the medium in which it is transported (atmosphere temperature profile) for a perfect gas as it is explained below.

1.4 . Mach Regimes

Mach number is a relation between the velocity of the study object and the speed of sound (eq. 3).

$$M = \frac{U_c}{a} \qquad (3)$$

Where M, U_c and a are the Mach number, the velocity of the study object and the speed of sound, respectively. (Anderson, 2003)

The speed of sound, for a perfect gas, is a function of temperature, given by:

$$a = \sqrt{\gamma RT} \quad (4)$$

Where T is the temperature of the medium in which it is transported. According to the velocity, Anderson classifies the Mach number as it is shown in Table 1.

Table 1
Mach number flow regimes

Mach Number	Flow regime
$0 < M < 1$	subsonic
$0.8 < M < 1.2$	transonic
$M = 1$	sonic
$1 < M < 5$	supersonic
$M > 5$	hypersonic

Source: Anderson, 2003

This paper includes within the interest field the supersonic flow and forwards, it is mean sonic, supersonic, and hypersonic flow regimes.

2. Supersonic Aerodynamics Theory

The supersonic aerodynamics behavior over a body depends on the geometry, and the fluid is analyzed as one-dimensional, two-dimensional or three-dimensional flow depending on each case

2.1. One–dimensional flow

According to Anderson, "a one-dimensional flow is one in which the flow field properties vary only with one coordinate direction" (Anderson, 2003). In this section is important to know the concepts about Stagnation point and Normal shock wave.

2.1.1. Stagnation Point

The total or stagnation points are considered to low decelerated isentropically. Else the equations of the isentropic flow are used with a final speed of zero. The relation is shown below:

$$\frac{T_0}{T} = 1 + \frac{\gamma-1}{2}M^2 \quad (5)$$

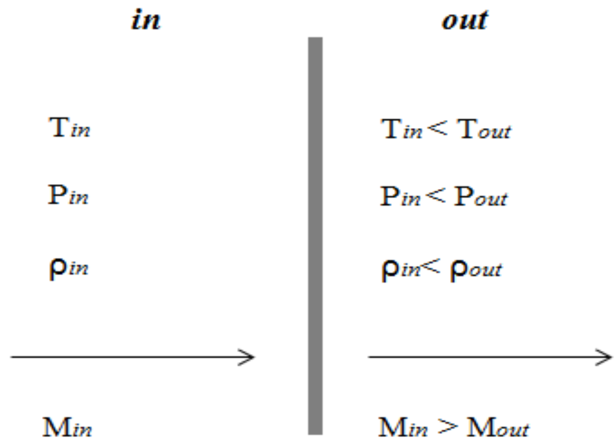
$$\frac{P_0}{P} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{\gamma}{(\gamma-1)}} \quad (6)$$

$$\frac{\rho_0}{\rho} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{1}{(\gamma-1)}} \quad (7)$$

2.1.2. Normal Shock wave

The normal shock wave is a discontinuity where the flow properties suddenly change creating a strong shock wave that separates the flow into two distinct regions (forward and behind the wave) (Figure 1) in a way that the temperature, pressure, and density are increased while the hypersonic/supersonic Mach number is decelerated to the subsonic Mach number behind it. Based on the continuity, momentum, and energy equations, the normal shock relations are given by (Anderson, 2003).

Figure 1
Normal shock
wave diagram



Source: Rodriguez, 2015 (adapted from Anderson, 2003.

Moreover, based on Anderson (2003) the normal shock relation is expressed in the equations eq 8, eq 9, eq 10, eq 11.

$$M_{out}^2 = \frac{1+\left[\frac{(\gamma-1)}{2}\right]M_{in}^2}{\gamma M_{in}^2 - \frac{(\gamma-1)}{2}} \tag{8}$$

$$\frac{P_{out}}{P_{in}} = 1 + \frac{2\gamma}{(\gamma+1)}\left(M_{in}^2 - 1\right) \tag{9}$$

$$\frac{\rho_{out}}{\rho_{in}} = \frac{u_{in}}{u_{out}} = \frac{M_{in}^2(\gamma+1)}{\left[2+(\gamma-1)M_{in}^2\right]} \tag{10}$$

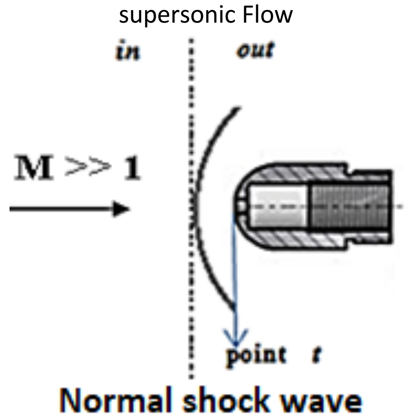
$$\frac{T_{out}}{T_{in}} = \left[1 + \frac{2\gamma}{(\gamma+1)}\left(M_{in}^2 - 1\right)\right]\left[\frac{2+(\gamma-1)M_{in}^2}{M_{in}^2(\gamma+1)}\right] \tag{11}$$

An important piece of equipment to measure velocity aerodynamically is the Pitot tube. It is a complement of the normal shock wave relation and stagnation point as follows.

2.1.3. Pitot tube

Considering a flow in front of a Pitot Tube with a blunt body geometry, placed in a hypersonic flow (Figure 2).

Figure 2
Pitot Tube in
supersonic Flow



Source: Rodriguez, 2015. (Adapted from Martos, 2014)

Initially, a normal shock wave is formed ahead of the body between points “in” and “out”. Since the flow downstream of a normal shock wave is always subsonic, the deceleration from point “out” to point “t” the velocity is zero and it can be assumed to be an isentropic process. Using this model of the flow, the pressure at the stagnation point can be calculated for any specified upstream conditions. (Oosthuizen and Carscallen, 1997)

The airflow at the Pitot tube entrance (point t) experiences a normal shock wave and isentropic flow, therefore the total pressure is given by:

$$\frac{P_t}{P_{in}} = \frac{P_t}{P_{out}}\frac{P_{out}}{P_{in}} \tag{12}$$

Replacing the known equations and variables and mathematically manipulating equation 9 (Rodriguez, 2015), the relation is expressed as:

$$\frac{P_t}{P_{in}} = \frac{\left[(\gamma+1)\frac{M_{in}^2}{2}\right]^{\frac{\gamma}{(\gamma-1)}}}{\left[\left(\frac{2\gamma M_{in}^2}{\gamma+1}\right)-\left(\frac{\gamma-1}{\gamma+1}\right)\right]^{\frac{1}{(\gamma-1)}}} \tag{13}$$

2.2. Quasi-one-dimensional flow

The Pitot tube is normally used in supersonic shock tunnels to measure the free-stream velocity in the test section after a convergent-divergent nozzle, where the fluid is considered quasi-one-dimensional.

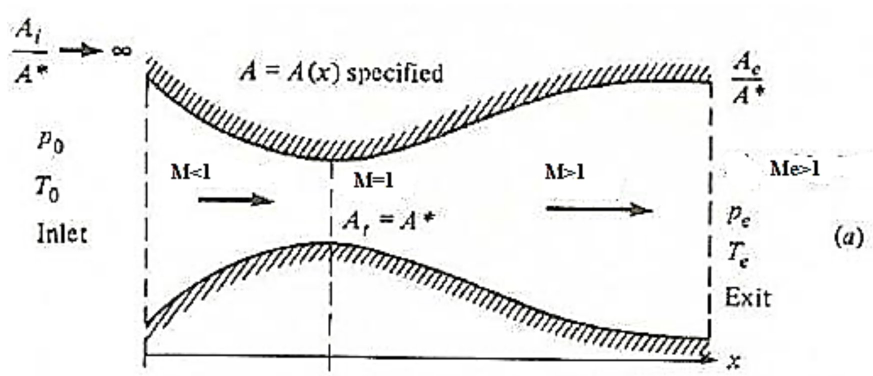
2.2.1. Convergent-Divergent Nozzle

Compressible Flow through a Convergent-Divergent Nozzle

Considering supersonic flow through a convergent-divergent nozzle, with initial properties at point ¨∞¨, followed by a critical point ¨*¨ in the middle of the throat where the flow is decelerated up to sonic speed and finally is accelerated up to supersonic speed at the end of the nozzle (Figure 3) (Anderson, 2003).

Figure 3

Convergent-divergent nozzle



Source: Rodriguez, 2015 (adapted from Anderson, 2003)

The Mach number of the flow in any position is a function of the area ratio between the local area and the throat area. The area ratio as a function of Mach number is given by:

$$\left(\frac{A}{A^*}\right)^2 = \frac{1}{M^2}\left[\left(\frac{2}{\gamma+1}\right)\left(1+\frac{\gamma-1}{2}M^2\right)\right]^{\frac{\gamma+1}{\gamma-1}} \tag{14}$$

Assuming an isentropic expansion, the ratio of the flow properties between the entrance point and the final point can be computed by the isentropic ratios. The final point of the nozzle is called free-stream conditions, there generally are placed body with various geometries, like wedge where it is possible to find a bi-dimensional flow.

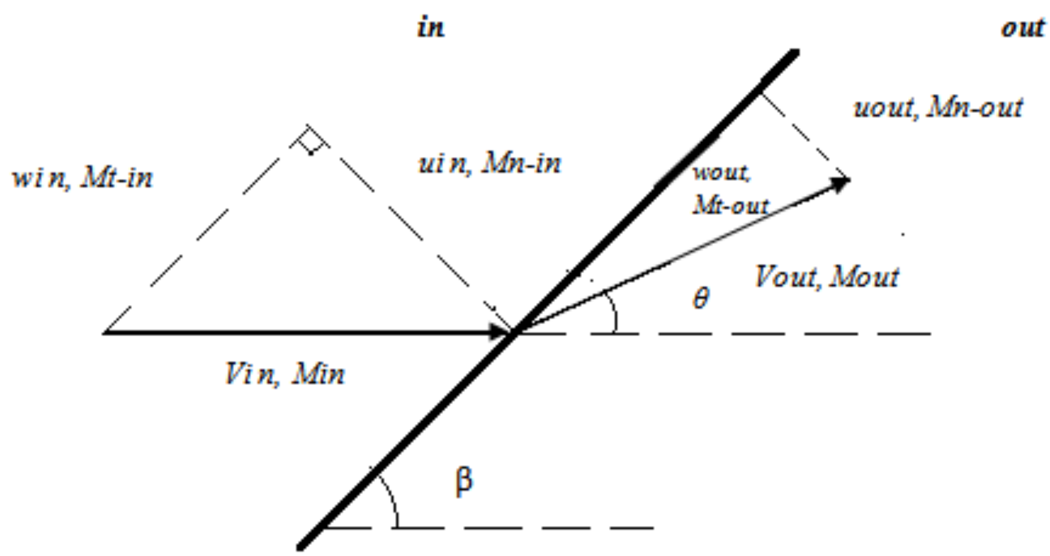
2.3. Two-dimensional flow

The mass, momentum, and energy conservation laws in two-dimensional steady-state, non-viscous, no heat conduction compressible flow must be applied to the oblique shock wave. The flow velocity is composed of the tangential and the normal velocities through the oblique shock wave.

2.3.1 Oblique Shock Waves

The tangential component is constant through the oblique shock wave (Figure 4). Therefore, the mass, momentum, and conservation laws may be applied to the normal component of the velocity, and considering the geometry of the oblique shock wave, it is possible to obtain the oblique shock relations (Anderson, 2001). For calorically and/or thermally perfect gas ($p = \rho RT\ \gamma =$ constant) the oblique shock relationships are obtained as a closed form of the thermodynamic property (static pressure, static density, and static temperature) ratios and Mach number across the oblique shock, given by:

Figure 4
The Supersonic flow
turned into itself



Source: Rodriguez 2015 (adapted from Anderson, 2003)

The governing equations of the oblique shock relation are expressed in the equations eq 15, eq 16, eq 17, eq 18 Anderson (2003).

$$\frac{P_{out}}{P_{in}} = 1 + \frac{2\gamma}{(\gamma+1)}[(M_{in}\ sen\beta)^2 - 1] \qquad (15)$$

$$\frac{\rho_{out}}{\rho_{in}} = \frac{(\gamma+1)(M_{in}\ sen\beta)^2}{(\gamma-1)(M_{in}\ sen\beta)^2+2} \qquad (16)$$

$$\frac{T_{out}}{T_{in}} = \left\{1 + \frac{2\gamma}{(\gamma+1)}\left[(M_{in}\, sen\beta)^2 - 1\right]\right\}\frac{(\gamma-1)(M_{in}\, sen\beta)^2+2}{(\gamma+1)(M_{in}\, sen\beta)^2} \quad (17)$$

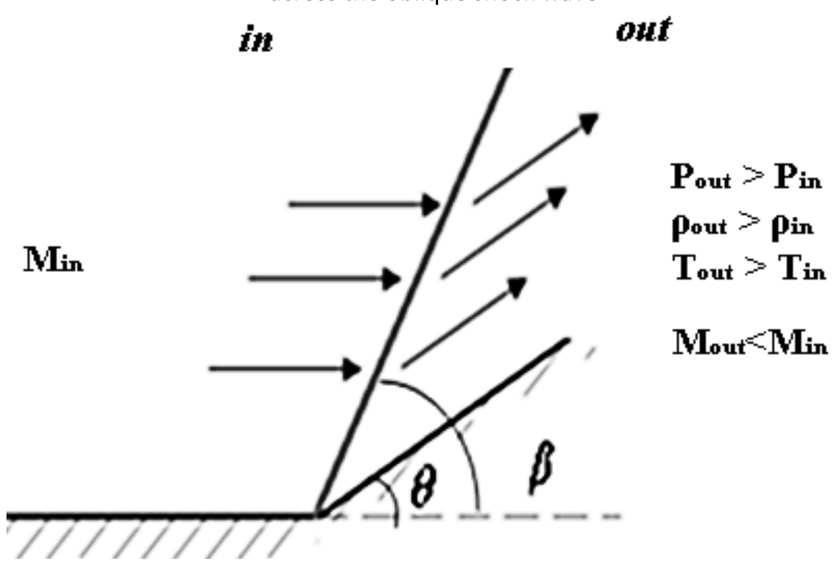
$$M_{out} = \frac{\sqrt{\frac{(M_{in}\, sen\beta)^2 + \frac{2}{(\gamma-1)}}{\frac{2\gamma}{(\gamma-1)}(M_{in}\, sen\beta)^2}}}{sen(\beta-\theta)} \quad (18)$$

Where: θ, β are the deflection angle of the body and shock wave angle, respectively. Additionally, the shock wave angle, β concerning the local flow direction θ may be obtained iteratively with the relationship given by:

$$tg\theta_s = 2(\mathrm{cotg}\,\beta)\left[\frac{(M_{in}\, sen\beta)^2-1}{M_{in}^2(\gamma+\cos 2\beta)+2}\right] \quad (19)$$

The flow across the oblique shock wave promotes an increase in pressure, density, temperature, and a decrease in Mach number (Figure 5). However, the flow remains supersonic/hypersonic and parallel to the flat surface of the external and internal compression section of the hypersonic vehicle with airframe-integrated scramjet engine lower surface.

Figure 5
Aerothermodynamics behavior
across the oblique shock wave



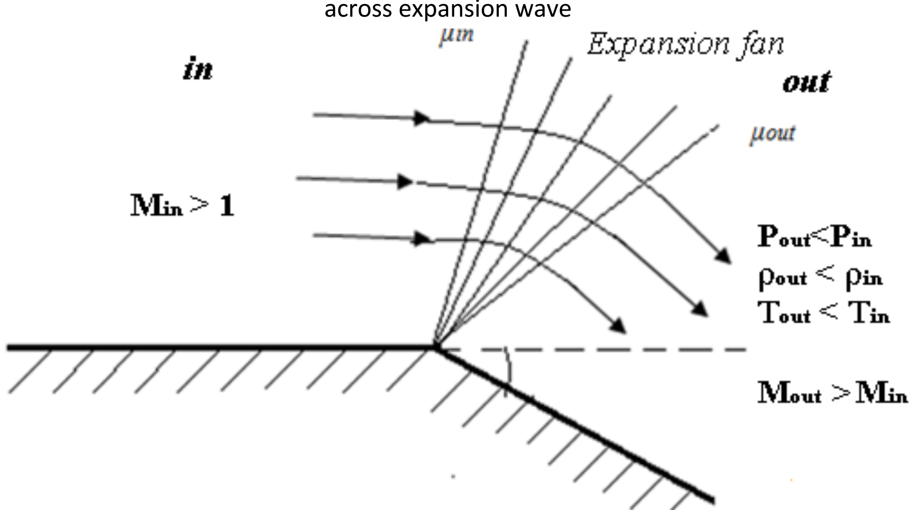
Source: Rodriguez 2015 (adapted from Anderson, 2003)

On the other hand, the bi-dimensional flow is also analyzed where the fluid is expanded and not compressed.

2.3.2. Expansion waves

The flow across the expansion wave promotes a decrease in static pressure, static density, and static temperature causing an increase in Mach number (Figure 6).

Figure 6
Aerothermodynamics behavior
across expansion wave



Source: Rodriguez 2015 (adapted from Anderson, 2003).

2.3.3 Prandtl and Meyer Theory

The Prandtl-Meyer theory (Anderson, 2003) may be applied to an isentropic expansion wave, which is limited by the head and tail of the expansion wave defined by the Mach angleμ_{head}, μ_{tail}, respectively.

The Prandtl and Meyer governing equations for the thermodynamic properties (Temperature, Pressure and Density) ratios across the expansion wave may be obtained by the isentropic relationships given by:

$$\frac{T_{out}}{T_{in}} = \left(\frac{1+\frac{\gamma-1}{2}M_{in}^2}{1+\frac{\gamma-1}{2}M_{out}^2}\right) \qquad (20)$$

$$\frac{p_{out}}{p_{in}} = \left(\frac{T_{out}}{T_{in}}\right)^{\frac{\gamma}{\gamma-1}} \qquad (21)$$

$$\frac{\rho_{out}}{\rho_{in}} = \frac{p_{out}}{p_{in}}\frac{T_{in}}{T_{out}} \qquad (22)$$

The Mach number after expansion wave is determined by an iterative process from the Prandtl and Meyer function $\upsilon\ (M)$:

$$\upsilon(M) = \sqrt{\frac{\gamma+1}{\gamma\text{-}1}}\ \ tg^{-1}\sqrt{\frac{\gamma-1}{\gamma+1}[M^2-1]} -\ tg^{-1}\sqrt{M^2-1} \qquad (23)$$

The Prandtl and Meyer function depends on the deflection angle θ_e as follow:

$$\theta_e = \upsilon(M_{out}) - \upsilon(M_{in}) \qquad (24)$$

Note that equation 23 has not a subscript, because it can be used for wave input and output.

2.4. Three-dimensional flow

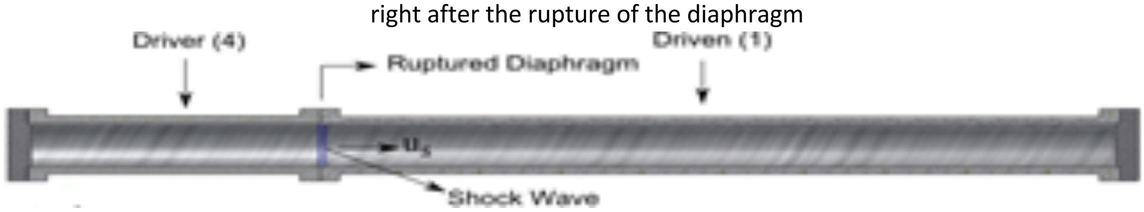
In supersonic flow over a cone, the flow area increases with increasing distance from the centreline. The flow between the cone surface and the conical shock wave is two-dimensional and cannot be analyzed using the simple procedures adopted in dealing with plane oblique shock waves. However, by using this fact, a relatively simple ordinary differential equation can be derived to describe the flow behind an attached conical shock wave. (Anderson, 2003)

3. Experimental supersonic aerodynamics

The high costs and risks of obtaining full data at well-defined test conditions are the limitations for flight tests of the supersonic systems, hindering severely the progress of its subsystems, components, and instruments. However, other methods, such as Computational Fluid Dynamics (CFD) and experimental investigations using ground test facilities, can be used to give partial information to the designers. CFD needs experimental data to provide ground test facilities and/or by flight tests to validate or modify the codes (Reddy et al., 1996). On the other hand, shock tubes and shock tunnels have been used as the principal tool for gas-dynamic research since the early '50s, both able to simulate high enthalpy flows at Hypersonic Mach numbers. Due to the short running time, the ground test requires special measurement techniques, to measure the thermodynamic properties of the flow field. (Petersen, 1998; Mantovani et al., 2011).

The Shock tube consists basically of the driver and driven sections, in general with constant cross-section area, separated by a single thin diaphragm (Figure 7). It is the most versatile experimental ground test of short duration facilities, which provides high enthalpy flows close to those encountered during the re-entry of a space vehicle into the Earth's atmosphere at hypersonic flight speeds (Lima and Toro, 2013).

Figure 7
Constant cross-section area shock tube
right after the rupture of the diaphragm

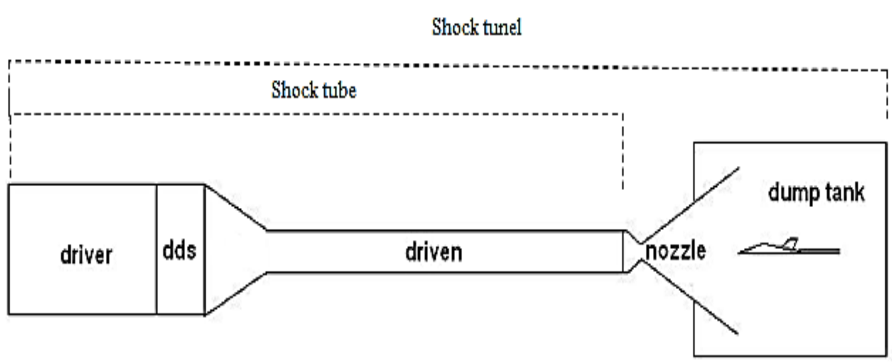


Source: Lima and Toro, 2013

The high-pressure section (Driver) and the low-pressure (Driven) section are pressurized at different pressures. When the diaphragm is broken, the gas in the high-pressure section expands towards the low-pressure section, causing the establishment of a normal shock wave that moves with speed "u_s"

A Hypersonic shock tunnel is a shock tube linked to a test section, which consists of the throat and the nozzle. The nozzle is used to accelerate the flow up to hypersonic velocity. Here is used the shock tube theory and the compressible flow through nozzle theory (Nagamatsu, 1958; Ferri, 1961; Minucci, 1991; Toro, 1998; Lima and Toro, 2013 and Anderson, 2001; 2003).

Figure 8
Hypersonic shock tunnel scheme



Source: Rodriguez, 20015. (Adapted from Rolim, 2009)

It is necessary to approach the fluid behavior within a shock tube and tunnel deeper, based on the information provided through this document. So far, aerodynamics' study has been considered theoretically and experimentally. However, the study of computational aerodynamics is an indispensable part of the design methodology for this type of system.

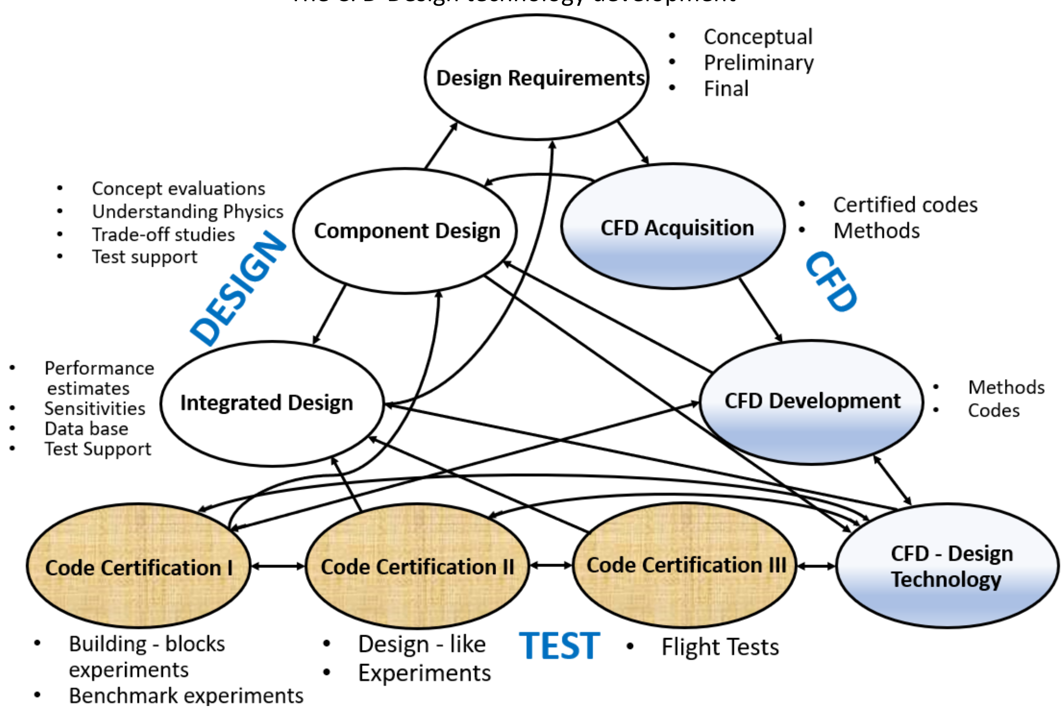
4. Computational Fluid Dynamics - CFD

Some aerothermodynamics environment properties and phenomena are not simple to compute form theory, like boundary-layer transition and turbulence, viscous-inviscid interactions, separated flows, nonequilibrium chemistry and the effects of surface catalycity, ablation, and non-continuum effects, among others. These phenomena are presented over bodies object of study and in supersonic shock tunnels.

For those cases where the research needs more complex analysis, computational tools are presented like a great solution, conducted from essential principles of the flow over practical geometry configurations, with hardware and software, computational fluid dynamics (CFD) plays an ever-greater role in the design process. (Figure 9) (Heisser and Pratt, 1994)

Figure 9

The CFD-Design technology development



Source: Heisser and Pratt, 1994

A design methodology normally is based on three principal factors, Theory, CFD and Test. Thus, is possible to approach a supersonic Aerodynamics learning path.

5. Methodology

Initially, this research is developed under the descriptive research methodology (Igwenagu, 2016), studying the supersonic Aerodynamics phenomena, to generate a learning path on existing theories like isentropic fluid, normal shock wave, oblique shock waves, expansion waves and total or stagnation conditions of the fluid.

Furthermore, analytical and numerical solutions (Lawson and Glenn. 2008) are proposed to solve mathematical government equations and relations. Insomuch as, CFD involves the behavior of a system and simulations methodology (Igwenagu, 2016) that is used, introducing variables, and collecting enough data to resemble reality. Typically evaluated with an absolute convergence criterion of "10e ^ (- 6)". In this way, considering these aspects, the student can be brought to an approximation of the entire discipline of supersonic aerodynamics. On the other hand, to develop the knowledge in supersonic shock tunnels and ground test facilities is necessary to use experimental research methodology (Igwenagu, 2016). This is applied in experimental researches concerned with the cause and effect, it´s the case of the fluid over the supersonic system surface in the test section.

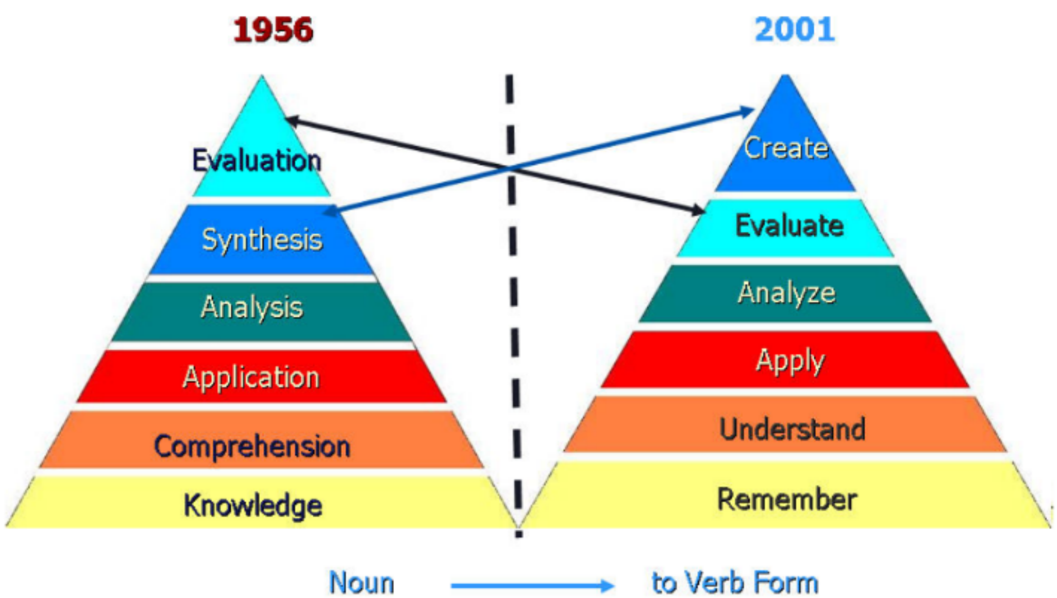
However, in addition to the descriptive methodology, it is necessary to have support in the execution of engineering education, whatever it may be. In this sense, it is necessary to take into account in this proposed path, a relationship between the student and the lecturer, this in order to obtain the relevance of what is planned in the course content, and determine through educational tools what really learned student, this can be demonstrated through continuous assessment of learning. In addition, it is necessary to consider the continuous improvement of content planning, which can be achieved with suggestions for improvement. Under this gaze, Bloom's taxonomy is used, in order to generate a reflection on the relevance of what the student has studied.

5.1. Blooms taxonomy revised

According to Bloom (Bloom, B. S., 1956) the major objective of purpose his taxonomy, is to facilitate communication and exchange information between persons within the educational framework. Understanding better the relationship between learning experiences and influence on students. The taxonomy provided six major categories in the cognitive domain: Knowledge, Comprehension, Application, Analysis, Synthesis, and Evaluation (Figure 10). (Krathwohl, D. R., 2002)

In 2001, Lorin Anderson and David Krathwohl, proposed a Bloom's taxonomy of educational objectives, listing or rewording the six major categories of the original Bloom's taxonomy from nouns to verbs as follow: (Anderson, L. W., Krathwohl, D. R., & Bloom, B. S., 2001).

Figure 10
Bloom vs. Anderson/Krathwohl Diagram

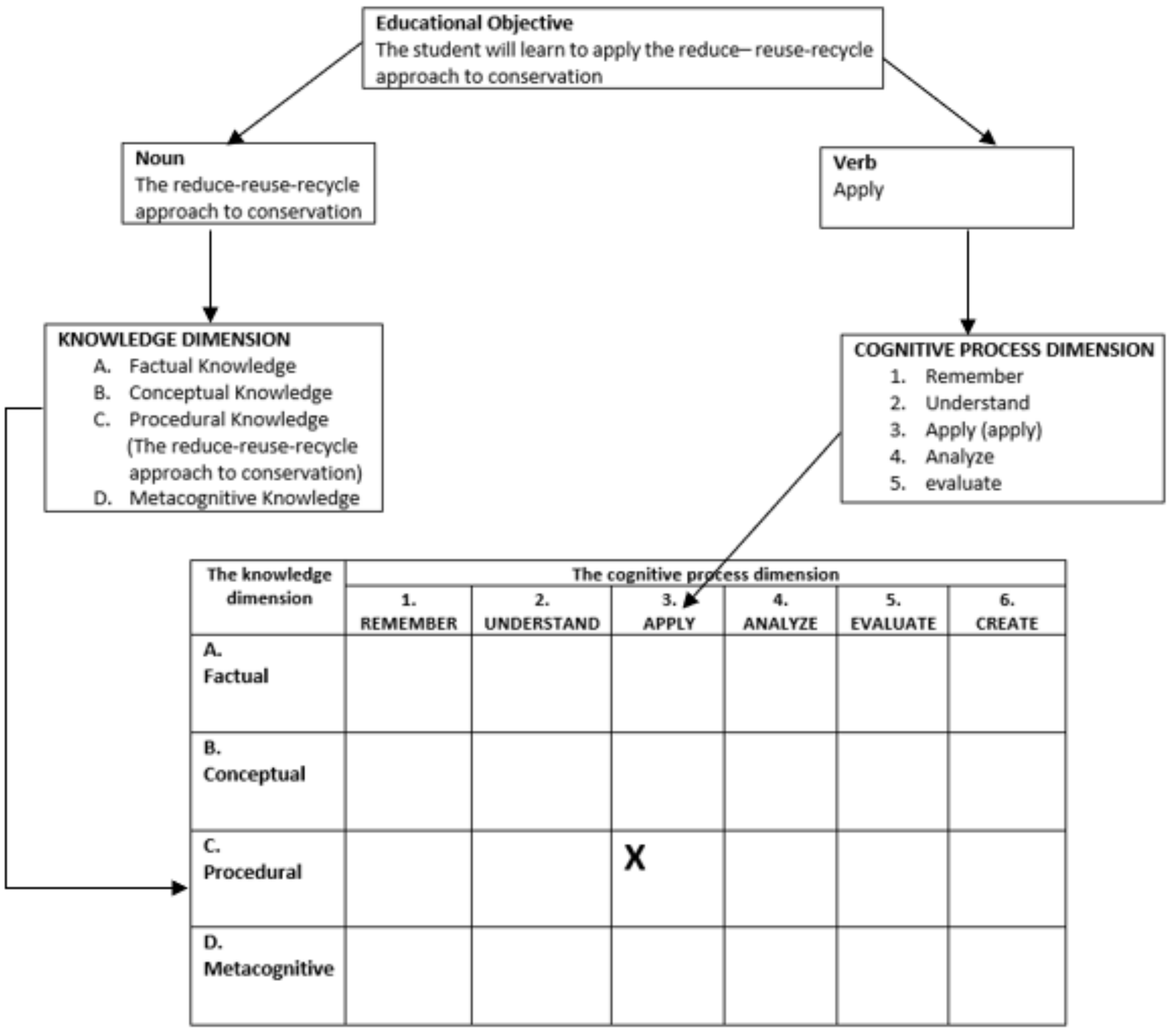


Source: (Wilson, Leslie O. 2001)

Additionally, Lorin Anderson and David Krathwohl, proposed “the taxonomy table” to explain deeply the Bloom´s taxonomy (Anderson, L. W., Krathwohl, D. R., & Bloom, B. S., 2001). The rows and columns of the table contain categories of knowledge and cognitive processes, respectively. Within the cells are placed the learning objectives to relate both categories.

Figure 11

How an objective (the student will learn to apply the reduce "reuse recycle approach to conservation) is classified in the taxonomy table.



(Anderson, L. W., Krathwohl, D. R., & Bloom, B. S., 2001)

In order to put in practice, the Bloom´s taxonomy, the educational objectives are included. The educational objectives are based on the work of Tyler (Ralph Tyler, 1949), "the most useful form for stating objectives is to express them in terms which identify both the kind of behavior to be developed in the student and the content". Therefore, the objective shall contain verbs to describes the intended cognitive process, and the noun to describes the knowledge students are expected to acquire or construct. Additionally, are considered the specificity of the objectives proposed by Krathwohl and Payne (1971), categorized by levels (Table 2).

Table 1
Relationship of Global, Educational,
and Instructional Objectives

	LEVEL OF OBJECTIVE		
	GLOBAL	EDUCATIONAL	INSTRUCTIONAL
SCOPE	Broad	Moderate	Narrow
TIME NEED TO LEARN	One or more years (often many)	Weeks or months	Hours of day
PURPOSE OR FUNCTION	Provide vision	Design curriculum	Prepare lesson plans
EXAMPLE OF USE	Plan a multiyear curriculum (e.g. elementary reading)	Plan units if instructions	Plan daily activities, experiences and exercises

Source: (Krathwohl and Payne 1971)

6. Supersonic aerodynamics under the gaze of Bloom's revised taxonomy

A route to learning Supersonic Aerodynamics aims to provide physical and mathematical tools to the student in the area of fluid mechanics. Through this path, students will learn to analyze the aerothermodynamic behavior of the compressible fluid on various geometries, and study bodies immersed in the stratospheric flight with Transonic, Supersonic, and Hypersonic flight regimes. Its focus is the global aerospace development and design by the incursion of air-breathing engines in military, civil and commercial aircraft prototypes.

According to the methodology described above, first, are defines the learning objectives.

6.1. Learning objectives

It is necessary to note that the structure of objectives is based on the Tyler and Krathwohl and Payne suggested. (Table 3)

Table 3
Learning objectives and specificity of the objective's relation

Learning objectives	**Specificity of the objectives**
1. The student shall be able to remember the physical principles of Continuity, Momentum, and Energy Equation about compressible fluids and the thermodynamics atmospheric properties and the atmospheric properties. (factual)	Global
2. The student shall be able to understand the compressible and expansion waves concepts over the supersonic system. (conceptual)	Global
3. The student shall be able to apply the government equations to compute the aerothermodynamics flow properties after compressible and expansion waves. (procedural)	Educational
4. The student shall be able to analyze the supersonic system operation in velocity profiles, from 1 to 26 Mach number in velocity and from 0 km to 86 km of altitude. (metacognitive)	Educational
5. The student shall be able to evaluate the supersonic system performance, based on pressure data measured in ground test facilities. (metacognitive)	Instructional
6. The student shall be able to create a document to explain novel solutions to solve problems of supersonic systems operation. (metacognitive)	Instructional

In order to accomplish the learning objectives below is proposed activities according to the subject.

6.2. Learning activities

According to the learning outcomes pretend, it is proposed activities in a learning guide as follows. (Table 4)

Table 4
Relation between activities and subject

Subjects	Activities
Basic fluid considerations Equations of fluid movement. Equations of continuity, momentum, and energy. Compressibility of the fluid. Speed of sound and Mach number. Navier-Stokes equations Properties of the standard atmosphere (1976 tables)	1. Read the information about basic fluid considerations and write an essay identifying the physical principles of Continuity, Momentum, and Energy Equations. 2. Produce an oral speech recalling the supersonic aerodynamics principles. 3. Make a summary relating to the thermodynamic properties of the atmosphere and the operating altitude of a given system.
1d flow and in pipelines 1-D flow, Normal shock waves. Shock waves in convergent and divergent nozzles by the 1-D flow. Isentropic fluid. Supersonic fluids in ducts of constant areas. Supersonic fluid on a pitot tube. Relationship of fluid properties through divergent convergent nozzles and pitot tubes. Introduction to supersonic ground test facilities. Operation of the supersonic ground test facilities. Compressive flow in propulsion, applications in Ramjets and Scramjets engines.	4. Read the one-dimensional flow concept from the book "Modern Compressible Flow" and create a document identifying the normal shock waves behavior and properties. 5. Read the information about supersonic fluid through divergent/convergent nozzles and pitot tubes and write a summary of the location and function in a supersonic shock tunnel. 6. Produce a working paper evaluating the aerothermodynamic properties throughout the ground test applied to supersonic systems. 7. Compute the aerothermodynamics properties after normal shock waves, using the government equations. 8. Produce a short oral presentation classifying the supersonic propulsion systems.
2d flow over supersonic profiles Supersonic profiles, Types and families. Theory of shock waves in profiles, general shapes, flat plate at supersonic speeds. Waves of oblique shock. Intersection waves. Intersection waves of opposite families. Intersection waves of the same family. Expansion Waves Prandtl theory - Meyer. Calculation of aerothermodynamic properties in high-speed two-dimensional fluids employing software.	9. Read the two-dimensional flow concept from the book "Modern Compressible Flow" and realize a summary identifying the oblique shock waves behavior and properties. 10. Read the expansion waves and Prandtl-Meyer theory from the book "Modern Compressible Flow" and create documents identifying the expansion shock waves behavior and properties. 11. Compute the aerothermodynamics properties after oblique shock waves, using the government equations 12. Compute the aerothermodynamics properties after expansion waves, using the government equations. 13. Produce a working paper evaluating the oblique shock and expansion waves throughout scramjet engines. 14. Write a working paper proposing a method to analyze the performance in real flight and ground test of supersonic systems.
Phenomena in 3d bodies Phenomena of 3D flows.	15. Read the three-dimensional flow concept from the book "Modern Compressible Flow" and create a summary identifying the conical shock waves behavior and properties.

Subjects	Activities
Equations of potential flow, conical bodies in supersonic flow,	
Hypersonic flow Boundary layer Heat transfer theory between undisturbed fluid and body surface. Theory of heat transfer distribution over a body. Statistical Thermodynamics	16. Research and read the high temperature effects in hypersonic flows and write a summary defining them. 17. Research and read the heat transfer theory and write a report identifying the fay and Ryddel theory, the B. J. Griffith and Clark H. Lewis theory, the Van Driest theory and the Lester Lees Theory. 18. Research and read the statistical thermodynamics concept and write a summary defining calorically perfect gas, thermally and real gas. 19. Compute the specific heat relation and flow properties in hypersonic flows based on the Tannehil and Muge method.
Computational fluid Dynamics - CFD	20. Create computational simulations over supersonic systems in operation. 21. To propose a flight profile of a supersonic system for leaving the atmosphere and one for re-entering the atmosphere, carrying out the analytical theoretical analysis, computational analysis and comparing the results.

6.3. Taxonomy table

Based on the taxonomy table previously described in the methodology.

Here is proposed a taxonomy table to develop a supersonic aerodynamics learning path. (Table 5)

Table 5
Supersonic aerodynamic taxonomy table

The knowledge dimension	The cognitive process dimension					
	1	2	3	4	5	6
F. K.	O (1) A (1) A (2) A (3) A (10) A (16) A (17) A (18)					
C. K.		O (2) A (4) A (5) A (8) A (9) A (15)				
P. K			O (3) A (7) A (11) A (12) A (19)			
M. K				O (4) A (6) A (13) A (14)	O (5) A (6) A (13) A (14)	O (6) A (20) A (21)

Is necessary clarify the terminology used as follow:

THE KNOWLEDGE DIMENSION

- F. K.: Factual Knowledge
- F. C.: Conceptual Knowledge
- F. P.: Procedural Knowledge
- F. K.: Metacognitive Knowledge

THE COGNITIVE PROCESS DIMENSION

- 1: Remember.
- 2. Understand.
- 3. Apply.
- 4: Analyze.
- 5: evaluate
- 6: Create

ACTIVITIES

- A (n): Activity (1), Activity (2), …, Activity (n)

LEARNING OBJECTIVES

- O (n): Objective (1), Objective (2), ..., Objective (n):

Finally, the taxonomy table proposed turns in a route to learning supersonic aerodynamics mixing the learning objectives, activities, and subject intended.

7. Conclusions

A route to learning supersonic aerodynamics consists in starting from the fundamental concepts of fluid mechanics and atmospheric flight. It is important to consider the flow regimes and the compressibility of the flow. It is also relevant to note that the aerothermodynamics properties in supersonic flows have input and output behavior, increasing or decreasing it, according to the specimen’s (object of study) geometry. In shock tubes and Laval nozzles this change based on area relations. Then it is necessary to analyze if the fluid is one, two, or three-dimensional according to each case. To follow a design methodology, after the theory it is necessary to include Computational Fluid Dynamics and direct the information to ground test facilities.

Generally, supersonic systems have an operation in a large range of Mach numbers from Supersonic to hypersonic speeds.

In supersonic fluid, the internal thermodynamic energy of the freestream fluid particles is small compared with the kinetic energy of the free stream for hypersonic flows. The high temperatures associated with hypersonic flight requires to consider the concepts of gas in Equilibrium: Thermal, Chemical, and Global. Additionally, the boundary layer, Reynolds number, Heat transfer theory between undisturbed fluid and body surface, Theory of heat transfer distribution over a body, and Statistical Thermodynamics. (Anderson, 2000; Anderson, 2001). To increase the development of a commercial and military aircraft, it is important to include in the design stages at universities the supersonic systems, due to these systems can reach hypersonic speeds, and also, it is necessary to consider phenomena as the viscosity and high-temperature.

About Bloom´s taxonomy revised proposed at this research, it´s a proposal to develop the necessary knowledge of engineering students to develop in the academic and professional field of supersonic systems research, the proposed activities are not compulsory, remembering that each teacher will be able to develop their strategies.

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