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Design of physical prototypes to analyze aerodynamic effects

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Abstract

The testing of physical prototypes is a critical step in the product design process since it allows detecting ignored faults and establishing actual manufacturing costs. By means of tests in experimental facilities, it is possible to obtain clarification on complex problems, to improve mechanical systems operation and to compare empirical results with theoretical models and numerical simulations data.

This work was aimed at designing of two different physical prototypes for specific purposes: a device to achieve the efficient atomization of a bulk liquid and vortex generators units to reduce drag in heavy trucks. In both cases, the involved aerodynamic phenomena will be comprehensively characterized in laboratory.

Special emphasis was put in the development of prototypes which were able to allow us making a wide number of distinct alternatives with low building costs. Thus, modular designs based on the quick exchange between parts, were carried out. In addition, simple geometry components and basic mechanical systems were proposed. In the two cases, up to 400 different configurations of study were obtained.

1 Introduction

From idea generation to production launch, the process of product design involves the development of numerous actions and the integration of different disciplines [1, 2]. In order to achieve final solutions as efficient as possible, the designer must know in detail materials, transform and manufacturing processes, product characteristics and users needs.

Design activities vary depending on the type of project and the type of innovation, but in many cases it is necessary the testing of a prototype to identify possible design deficiencies. As fig. 1 shows, the study of different prototype alternatives is performed within a process that it is carried out iteratively to achieve the best design. This process is called as design-build-test cycle [3].

Computer simulations and rapid prototyping [4] are, at present, usual strategies to find strengths and weaknesses of an initial design with a significant reduction of time needed for physical prototype building. Nevertheless, numerous problems related with the study of fluid mechanics and particularly, with the analysis of aerodynamic phenomena, require the development and trying of specific physical prototypes. Operation and technical performance of these prototypes are tested in controlled investigation labs using experimental methods.

On the other hand, modularity is an important technique of product conception, which can minimize environmental loads and costs during the whole life of a product [5], improving, for example, maintainability and reusability. Modularity application to the design process implies the following general steps: decomposing the product into simple parts, analyzing the interactions between parts, and selecting assembly-disassembly methods.

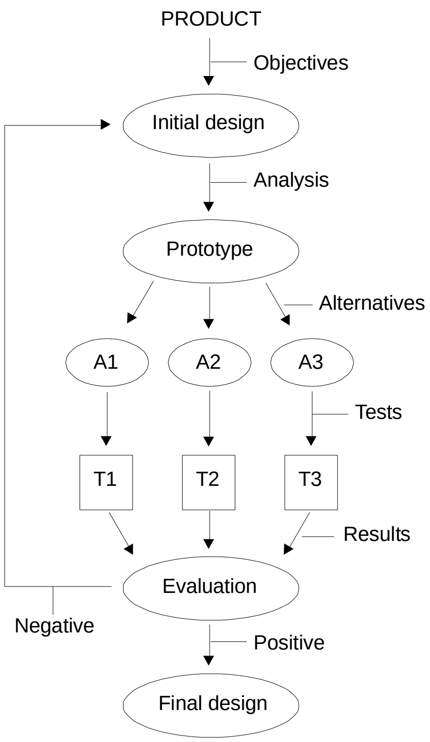

Fig. 1. Process of product design

Experiments in physical prototypes suggest that relevant design parameters could be varied independently. If prototype is based on a modular design and each parameter is associated with a simple part, different configurations of study can be obtained, with relative low costs, via the exchange of elemental parts [6].

According to this methodology, two different physical prototypes were developed. Final designs are presented in this work. First, a twin-fluid atomizer prototype to generate a fine spray is presented. Following, vortex generators units to obtain aerodynamic improvements in heavy vehicles are shown. In both cases, modularity applied to prototype design, allowed obtaining a big number of different alternatives, which can be analyzed in detail through experimental methods.

2 Atomizer prototype

Atomizers are device used to transform a bulk liquid into a dispersion of small droplets. They are usually found in numerous industrial processes and in many other applications as agriculture, meteorology and medicine. Thus, it is important for engineers to acquire a better understanding of the basic atomization process, to know which type of atomizer is best suitable for any given application and how the performance of any given atomizer is affected by variations in liquid properties and operating conditions.

2.1 Atomization principles

The disintegration of a bulk liquid may be achieved in various ways [7]: by the kinetic energy of the liquid itself or by exposure to high-velocity air or gas, or as a result of mechanical energy applied externally through a rotating or vibrating device. The method which exposes a relatively slow-moving liquid to a high-velocity airstream is generally known as twin-fluid, air-assist or airblast atomization (fig. 2). Atomizers based on this operation method are used in dispersing liquid fuels for combustion, gas-liquid mass transfer applications, food processing, spray drying of wet solids, paint spraying, etc.

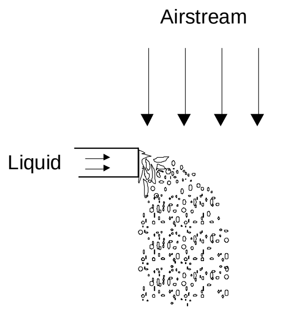

Fig. 2. Liquid atomization by exposition to a high-velocity airstream.

The liquid disintegration process in twin-fluid atomizers is dependent on the energy transfer from the high velocity gas stream to the relatively low velocity liquid stream. In addition, energy transfer is more efficient when initial liquid is in the form of thin sheets or small columns. Hence, spray characteristics are markedly affected by the internal geometry of the atomizer [8].

2.2 Twin-fluid atomizer characteristics

In this work the design of a twin-fluid atomizer prototype was carried out in order to analyze by experimental methods how the internal aerodynamic affects the liquid atomization. In general, the study of the fluid dynamic flows within twin-fluid atomizers is highly complex due mainly, to interaction phenomena, liquid disintegration and intense mixing of gas and liquid.

This atomizer employed very high air velocities that necessitated an external supply of high-pressure air. The following characteristics were specified for the internal atomizer geometry:

- Air injection through tangential inlets.
- Air-flow acceleration into a conical swirl chamber.
- Liquid supply through small axis-normal holes.
- Axial spray exit.
- Atomizer core occupied by a cylindrical element.

Fig. 3 shows the internal geometry of the twin-fluid atomizer and the parameters needed to characterize it.

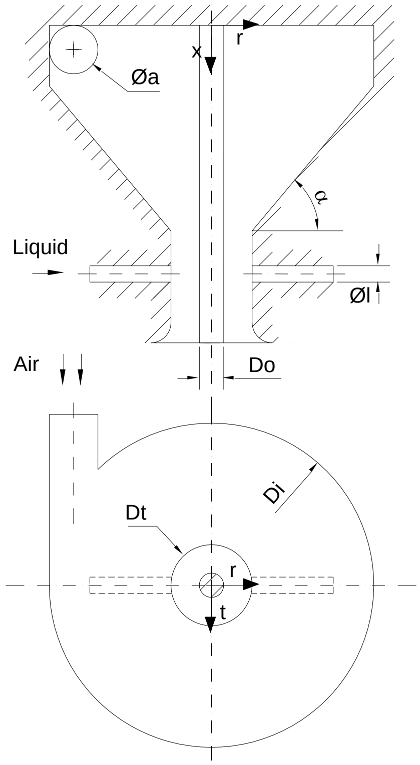

Fig. 3. Internal geometry of the twin-fluid atomizer.

2.3 Prototype design

According to the characteristics previously specified, an atomizer prototype made up by four different parts (fig. 4) was proposed. These simple parts were named:

1) Cover;
2) Chamber;
3) Exit;
4) Nucleus;

Prototype assembly-disassembly was easily performed by means of socket cap screws. Additionally, some sealing joints between parts were added.

The modular conception of the prototype, such as it is appreciated in fig. 4, allowed the characteristic parameters of the atomizer to be varied independently.

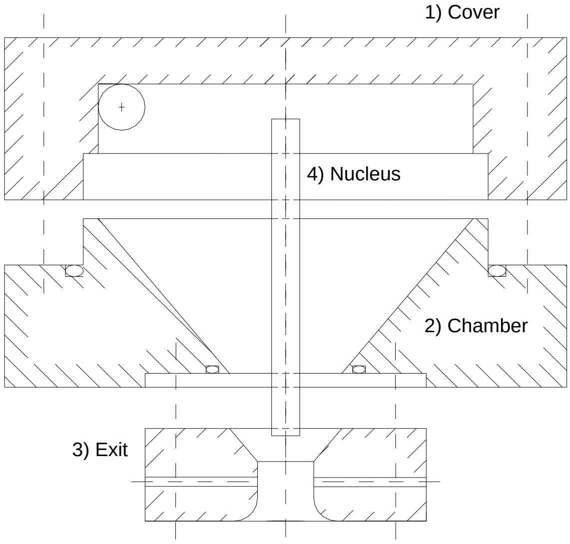

Fig. 4. Elemental parts of the twin-fluid atomizer prototype.

Each atomizer-part was associated with a different characteristic parameter. Thus, the cover-part was associated with the size of the air tangential ports, the exit-part with the throat diameter and the nucleus-part with his diameter (fig. 5). The geometry of the swirl chamber was fixed in this case.

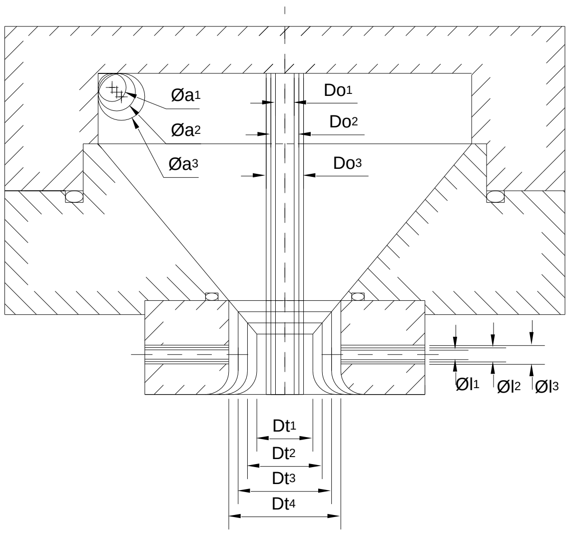

Fig. 5. Variation of the internal geometry parameters.

A total number of eleven different components, which included three covers, one chamber, four exits and three nucleuses, made up the atomizer kit and allowed the modification of internal parameters within a sufficient range.

Tab. 1 shows the most important parameters involved in the prototype design and the specific notation used for describing the different alternatives that can be selected within each parameter.

It should be taken into account that:

- Every cover-part was designed to inject air through four tangential air ports, but options with one or two ports can be also studied if some of them are blocked.
- The size of the liquid supply inlets can be changed by means of standard tubes.
- Other prototype configurations can be obtained if the central cylinder is not used.

Design parameter	Alternatives				Number
Air ports number	N1	N2	N4		3
Air ports diameter	$\varnothing a^1$	$\varnothing a^2$	$\varnothing a^3$		3
Throat diameter	Dt^1	Dt^2	Dt^3	Dt^4	4
Nucleus diameter	-	Do^1	Do^2	Do^3	4
Liquid holes diameter	$\varnothing l^1$	$\varnothing l^2$	$\varnothing l^3$		3
				Total	432

Tab. 1. Alternatives of study for each design parameter.

A total number of 432 prototype configurations can be obtained using all the alternatives of study exposed in Tab. 1. Any test configuration can be coding via the addition of the specific notation used for each parameter. For example, the global code $N2\varnothing a^1 Dt^1 Do^2 \varnothing l^1$ can be used to identify the following particular atomizer configuration: cover-part with air injection through two tangential ports of $\varnothing a^1$ diameter, exit-part with Dt^1 throat diameter, nucleus of Do^2 diameter and liquid supply through holes of $\varnothing l^1$ diameter.

An exhaustive study of the different prototype configurations is being currently carried out in an experimental setup (fig. 6). Spray characteristics and particularly the droplet size distributions are being measured by means of non-intrusive optical methods. Since systems based on the light scattering are very appropriate for a relatively rapid characterization of droplet sizes, a laser diffractometry is being used to analyze how the spray characteristics are affected by the internal geometry of the atomizer.

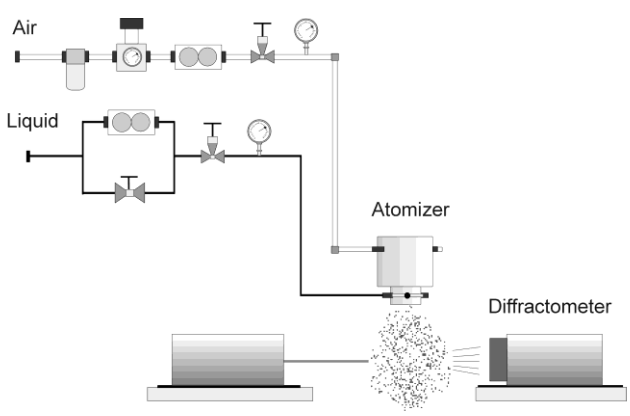

Fig. 6. Schematic of the experimental setup.

Proposed strategies for the future [9] include the simultaneous experimentation with interactive model predictions. Nevertheless, experimental studies with physical prototypes are still the only reliable source of knowledge of the droplet size distribution in sprays.

3 Vortex generators prototype

Aerodynamics studies the airflow around solid objects and enables the calculation of forces and moments acting on them. It acquires a great relevance in the truck industry, in order to obtain more energy-efficient and less polluting vehicles.

Diverse methods can be applied to reduce aerodynamic drag in vehicles: varying their external design, changing the superficial finish, adding aerodynamic improvements and diminishing tolerance between component parts. All these strategies are specially recommended for vehicles that travel regularly at high speeds, since aerodynamic power depends on the cubing of speed.

Furthermore, a more aerodynamic vehicle also increase their stability and decrease the effects of aerodynamics on other vehicles travelling on the same road, as well as diminishing splashing and improving the vehicle's resistance to lateral winds, etc.

3.1 Aerodynamic improvements in vehicles

In recent years the external appearance of vehicles has undergone great changes with the purpose of reducing both, the transversal area and the aerodynamic penetration coefficient. The straight lines of yesteryear have been replaced with new and sinuous shapes and more stylized profiles.

Over the last thirty years, the average penetration coefficient of automobiles has gone down by 40%, an improvement which has brought about a 19% reduction in fuel consumption. However, similar significant developments in relation to the aerodynamics of larger sized trailers have not taken place and different initiatives are now in study [10].

Tab. 2 shows, classified by vehicle zones, the main aerodynamic improvements which are being currently used in trailer trucks.

Tractor head	Trailer	King-pin space	Wheels
Rounded corners Air deflectors Vortex generators	Rounded edges Vortex generators Boat-tails	Spoiler Lateral air deflectors Cab extensions Trapped vortex Fairings	Undercarriage skirt Alignment Air dam

Tab. 2. Aerodynamic improvements in trailer trucks.

One of these improvements consists on the installation of vortex generators (VGs) in two specific zones of the vehicle: in the rear of the head tractor and in the rear of the trailer (fig. 7). Locations at the top of the tractor and the trailer were denoted as Z1 and Z3, respectively. Similarly, lateral locations in the vehicle were denoted as Z2 and Z4. Aerodynamic effects on the vehicle can be analyzed for each individual location or if some of them are combined. The total number of possible alternatives of study is 24.

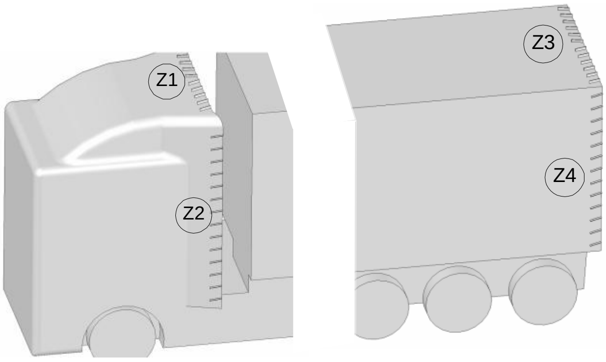

Fig. 7. Location of vortex generators in the trailer truck.

Vortex generators are small bumps on the vehicle surface which have as objective to delay the boundary layer separation. A vortex generator creates a vortex tip which draws energetic and rapidly-moving air from outside the slow-moving boundary layer into contact with the vehicle [11].

Commonly used on aircraft (fig. 8), vortex generators themselves create drag, but they also reduce drag by preventing flow separation at downstream. The overall effect can be calculated by totalling the positive and negative effects.

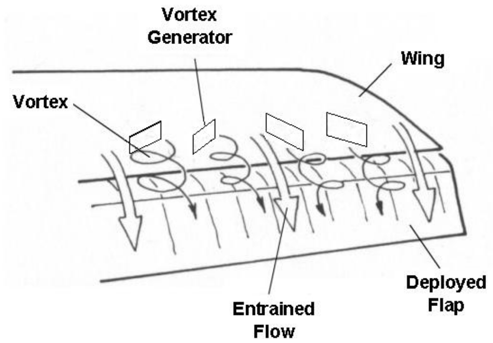

Fig. 8. Vortex generators on an airplane wing.

3.2 Prototype design

Prototypes of vortex generators units (VGs units), to improve the vehicle aerodynamic were designed. In order to obtain the total wide and height of a trailer truck, two different VGs units, with a length of 400 and 200 mm, respectively, were considered.

The standard dimensions of the most frequently used vehicles are 2.4 to 2.5 m wide and 2.45 to 2.7 m high. In this case, a trailer 2.4 m wide and 2.6 m high was utilized as suitable reference (fig. 9). Thus, a total of six 400 mm long VGs units were required to obtain each trailer dimension and an extra unit 200 mm long was needed to complete the trailer high.

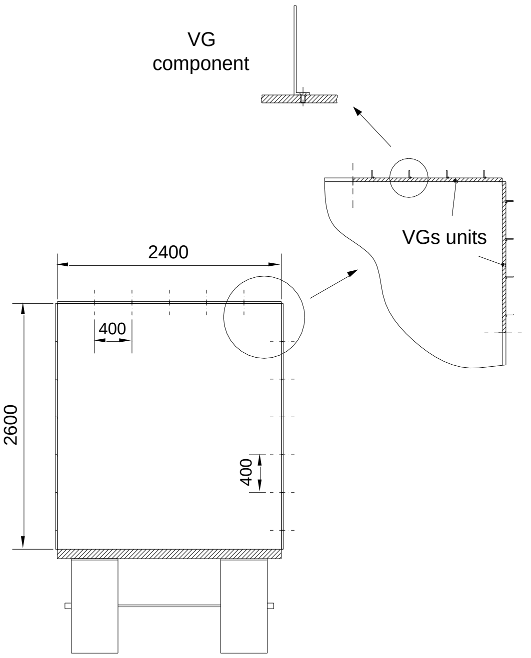

Fig. 9. Vortex generators installation.

The following variables were considered essential in the design process of a VGs unit:

- Geometry of each VG component.
- Space between VGs.
- Angle of each VG component with respect to the airflow velocity.

Regarding the geometry of components, three different types of VGs were proposed (fig. 10): a) rectangular; b) triangular and c) aerodynamic. Total length and height of each component type was fixed.

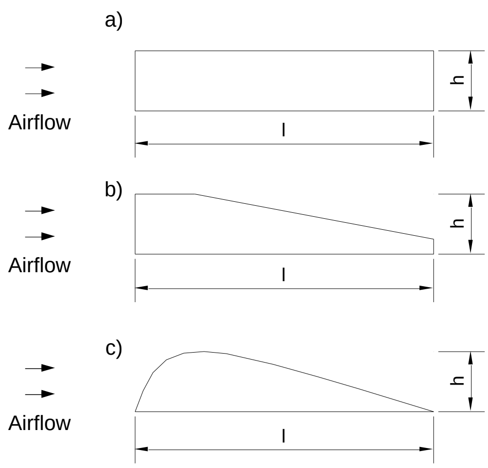

Fig. 10. VGs geometry types.

The design of a VGs unit was performed allowing the exchange between VGs geometry types, as well as the testing of two different spaces between VGs. Minimum and maximum spaces were 100 and 200 mm, respectively. Therefore, a total number of 4 components can be placed in a 400 mm long VGs unit (fig. 11).

The angle of each VG component with respect to the local airflow, which is called angle of attack, can be changed in the prototype. Thus, three different configurations of study can be obtained:

1) VGs parallel to the airflow.
2) VGs at an angle α with respect to the airflow.
3) VGs alternately deflected an angle α with respect to the airflow.

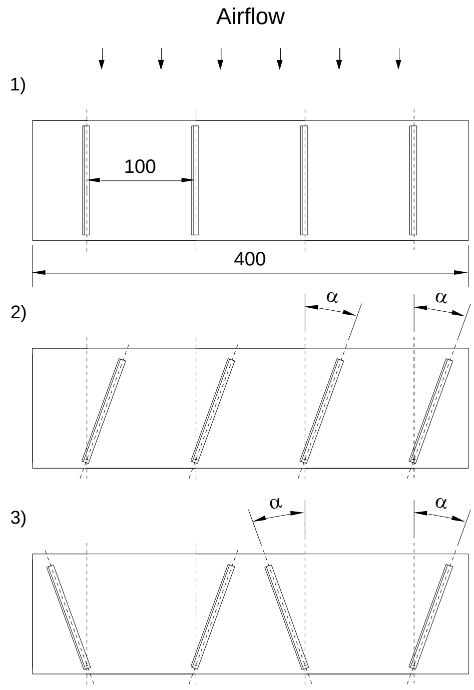

Fig. 11. Angles of attack in a 400 mm long VGs unit.

Tab. 3 shows the variables involved in the prototype design and the notation used for describing the different alternatives of study. The three types of VGs geometry were denoted as R, T and Ae, respectively and the three different configurations resulting of the angle of attack change were correspondingly designated as A1, A2 and A3. Taking into consideration two different angles for the A2 and A3 cases, a total number of 30 configurations of study can be obtained.

The combination of both, VGs locations in the vehicle and VGs units' configurations, give us a total number of 720 possible different alternatives of study, which can be tested in a wind-tunnel.

Design variable	Alternatives					Number
VGs geometry	R	T		Ae		3
Space	s1	s2				2
Angle of attack	A1	A2		A3		5
		α1	α2	α1	α2	
					Total	30

Tab. 3. Alternatives of study for each design variable.

Any alternative object to study can be coding via the addition of the specific notation used for each variable. For example, the global code Z1Z3RS1A2α1 should be used to identify the following configuration of study: VGs units located at the top of the tractor and the top of the trailer, composed by rectangular type components spaced 100 mm and all deflected at an angle of attack α1 with respect to the airflow.

Prototypes are still in development. Experiments will be performed with specific configurations according to results achieved by numerical simulations, which are now in progress.

Intended tests will consist on the visualization of the flow around vortex generators and the determination of the velocity field using high-resolution optical techniques as phase Doppler anemometry and particle image velocimetry. In both techniques, measurements are based on the analysis of the signals of very small particles, which supposedly follow the instantaneous changes in air velocity. Further details of these measurement techniques can be consulted in a number of works [9].

4 Conclusion

In this work, two physical prototypes to analyze aerodynamic effects were designed. A twin-fluid atomizer of wide application and vortex generators units to install in a trailer truck were proposed. Mechanical simplicity and modularity were applied as design strategies in order to obtain a high number of different prototype configurations with relative low building costs. Any configuration could be easily identified during the tests via the use of a specific notation.

The atomizer prototype was made up by four different exchangeable parts and their design allowed the variation of the relevant internal geometry parameters in an independent form. Experimental studies of the resulting sprays, including measurements of the droplet size distributions, are being currently carried out in lab.

Prototypes of vortex generators units were formed by a set of small bumps and were placed in the rear of the head tractor and the trailer in order to improve the vehicle aerodynamic. Design allowed the variation of vortex generators geometry, the space between individual components and the angle of attack with respect to the airflow velocity. In agreement to numerical simulations, a certain number of alternatives will be experimentally studied.

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