A Laser System For Cryogenic Wind Tunnels

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ABSTRACT

Cryogenic wind tunnels have been under active development for several years only. The main advantage of this type of tunnels is the possibility of obtaining high values of Reynolds number on relatively small test models. Moreover, it offers massive reduction of energy required in transonic and low speed testing.

The basic idea of the cryogenic wind tunnel is to obtain flow at very low temperature in the order of 120°K . This temperature is reached by injecting liquid nitrogen in the circuit of the tunnel. In order to reach correct simulation of flow on the tested model, the particles of liquid nitrogen must be evaporated completely on entering the test section of the cryogenic wind tunnel.

This paper presents a laser system developed to determine the size-distribution of liquid nitrogen particles carried in the airstream of a pilot cryogenic wind tunnel. The developed system could be used to determine size distribution functions of particles in aerosols, combustion and in a two-phase-flow (liquid-gas) generally. It is actually feasible to be applied in this area of experimental investigations.

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INTRODUCTION

The cryogenic wind tunnel has been under active development for several years only. There are two major advantages of this new type of tunnels. The first is the possibility of obtaining high values of Reynolds number on relatively small test models. The second major gain is the massive reduction of energy required in transonic and low speed testing.

References 1,2 and 3 show that the energy required for a low - speed testing at high Reynolds number (15 millions) in a cryogenic wind tunnel is not more than 1,55 % of the energy required for the same testing in a conventional wind tunnel, moreover, the dimensions of the test section of the cryogenic tunnel are reduced to be only 17 % of the other type.

In the case of transonic testing at high Reynolds number (40 millions) the energy required for the cryogenic tunnel is 2 % of the energy required for the same testing in a classical one. In addition, the dimensions of the measuring section of the cryogenic tunnel is equal to 20 % only of that of the conventional wind tunnel. It is evident that the testing models are of smaller size.

The basic idea of a cryogenic wind tunnel is to obtain high values of Reynolds number by reducing the temperature of the airstream to be in the order of 120 °K. This very low temperature is reached by injecting liquid nitrogen in the circuit of the tunnel. In order to reach correct simulation of fluid flow on the tested model, the injected particles of liquid nitrogen must be evaporated completely on entering the measuring section of the cryogenic wind tunnel.

Therefore, a laser system is designed and manufactured to determine the size-distribution of liquid-nitrogen particles carried in the airstream, their volumetric concentration and mean diameters at different working conditions. This experimental investigation could help in understanding the evolution of size of tested particles, phenomena of evaporation and or collision along the axis of the measuring section of the cryogenic wind tunnel.

This system is introduced in references 4 and 5. There are some troubles and difficulties appeared on using this system in the experimental investigation. Adjusting of this system is one of the major disadvantages that limited the capabilities of the system.

This paper presents a modification of the laser system mentioned before, to overcome the main troubles appeared on its utilisation in the laboratory. Theoretical concepts of the system is kept without any major modification.

THEORETICAL CONCEPT

Reference 5 introduces the basic concept of the laser system, but it is repeated very briefly in this paper for completeness.

Let $f(r)$ be the size distribution function (in number) of particles. The total number of particles per unit volume is then equal to $\int f(r) dr$. The intensity $I(\theta_i)$ of monochromatic light scattered by a spherical particle of radius r in a given direction θ_i is proportional to the differential scattering cross section $\sigma(r, \theta_i)$. Hence, the scattering cross section per unit volume in the direction θ_i is expressed by the following equation

$$\beta(\theta_i) = \int_0^{\infty} \sigma(r, \theta_i) \cdot f(r) dr \quad (1)$$

The term $\beta(\theta_i)$ is determined experimentally by measuring of the intensity $I(\theta_i)$ using the laser system presented in this paper. The term $\sigma(r, \theta_i)$ is the kernel of an "ill-conditioned" or "improperly-posed" integral equation (1) of Fredholm type. The unknown distribution function (in number) $f(r)$ has to be determined.

The method of solution of the "ill-conditioned" integral Eq. (1) is the following [5]:

Consider the radius of particles is equal to $r = kx$. Multiplying and dividing the kernel by e^x , then Eq. (1) could be written in the following form:

$$\beta(\theta_i) = \int_0^{\infty} e^{-x} \cdot Y(x) dx \quad (2)$$

where

$$Y(x) = k \cdot \sigma(r, \theta_i) F(r)$$

$$F(r) = e^x f(x)$$

$$k = \text{scale factor}$$

Then, the Gauss-Laguerre quadrature of the form [6]

$$\int_0^{\infty} e^{-x} f(x) dx = \sum_{j=1}^n H_j \cdot f(a_j)$$

is applied to Eq. (2) which results in the equation of the form:

$$\beta(\theta_i) = \sum_{j=1}^n A_{ij} G_j \quad (3)$$

where

$$A_{ij} = k H_j \cdot \sigma(r_j, \theta_i)$$

$$G_j = f(r) \cdot \exp(-a_j)$$

The weight coefficients H_j are determined by the following equation [6] :

$$H_j = (n!) / a_j L_n(a_j)$$

$L_n(a_j)$ are Laguerre polynomials of order n and their roots are a_j . The order n is not more than the number of directions determined by the number of mirrors of the laser system. Numerical values of weight coefficients H_j and roots of the Laguerre polynomials $L_n(x)$ are presented in reference 6.

Applying the inverse technique of Twomey [5] to Eq. (3) the matrix equation obtained has the following form:

$$G = (A^T A + \gamma C^T C)^{-1} A^T B$$

Solving this matrix equation, there are n -discrete values of the size-distribution function (in number) determined by the following equation:

$$f(r) = G / \exp(a_j) \quad (4)$$

The volumetric distribution function per unit volume can be expressed by the form:

$$g(r) = 4/3 \cdot \pi \cdot r^3 \cdot f(r) \quad (5)$$

The total volumetric concentration is defined by the equation

$$C_T = \int_0^\infty g(r) dr \quad (6)$$

The error of the Gauss-Laguerre quadrature is determined by Eq(7)

$$E = [(n!)^2 / (2n)!] f^{2n}(n) \quad (7)$$

It is found that this error E is less than the error of the solution of the "ill-conditioned" integral equation (1) because it has the following characteristics:

- a- it may have no solution,
- b- without considering supplementary hypothesis, it may have several solutions,
- c- there is no stability of solutions i.e. any error in $\beta(\theta_i)$ determined experimentally, may lead to a solution quite different from the correct one.

Hence, one has to choose the solution that gives the lowest error in the recalculated values of $\beta(\theta)$. This error must be inferior to 10 % that is due to the "speckle" of the laser beam.

DESCRIPTION OF THE LASER SYSTEM

The laser system presented in this paper is shown on figure 1. The basic idea of the system is explained in the following paragraphs:

- On the upper edge of a vertical flat plate a laser tube is fixed. The laser source used is He-Ne (wave length equals to $0,4880 \mu\text{m}$ and one watt of power).
- A system of plane mirrors, fixed perpendicularly on the flat plate, are distributed tangentially to an ellipse where each mirror makes an angle θ_i with the major axis of the ellipse. On the focus of the ellipse, a plane mirror inclined by 45° rotates about the focus by means of a small electric motor of 50 Hz.
- The plate is placed vertical to the plane of the circuit of the wind tunnel. The center line of the test section must be on the second focus of the ellipse.
- The laser beam, emitted from the laser tube, is reflected twice before crossing the test section of the tunnel. The particles of liquid nitrogen carried in the airstream of the tunnel scatter the monochromatic light in all directions. The scattered light in the plane of the flat plate only is reflected on the system of distributed mirrors. Then the light is collected on the rotating mirror because it is located in the first focus of the ellipse. According to the geometrical principle of the ellipse, the distance travelled by the scattered laser is constant.
- The collected light by the rotating mirror is detected by a photomultiplier then amplified by a logarithmic amplifier. Then it is registered on a magnetic tape or on an oscilloscope. The diagram of signals registered is known as " Scattering Diagram " (Fig. 3) .

On analysing " Scattering Diagrams " obtained by the laser system, the left hand side of Eq.(1) is determined because the scattering diagram represents the intensity of monochromatic light scattered in the direction of θ_i .

The computer program developed calculates the kernel of the integral equation(1) $\bar{G}(r, \theta_i)$ by using the Mie theory for given wavelength of the incident laser beam and given index of refraction of the tested particles. Then, it computes n-values of the size distribution function(in number) $f(r)$ using the method of solution described in the previous section. Volume-distribution function $g(r)$ is determined and the total concentration of particles too. Necessary mean diameters as diameter of Sauter $\bar{D}_{32}$, De Brouckere diameter $\bar{D}_{43}$ and the volume diameter $\bar{D}_{31}$

are calculated in each measurement. The program is executed in double precision. The required values of the kernel $\bar{G}(r, \theta_i)$ are calculated in advance by another separate computer program.

MODIFICATION OF THE LASER SYSTEM

Figure 2 presents the initial laser system before the modification. In this system the laser tube is not connected to the flat plate. It is placed on the other side of the test section i.e. not on the same side as the plate with the system of mirrors. This is the major disadvantage of that system which was designed and constructed in the laboratory as a first version. This system must be adjusted just before each measurement and it must be checked even during the measurement itself. The process of adjusting of the system is actually time consuming and associated with several difficulties.

It is not convenient to use this initial device in the experimental investigation of evolution of size-distribution of particles along the axis of the test section of the wind tunnel. The device could not be shifted during the testing. The permitted dimensions of the measuring room are relatively small, not more than $60 \times 120 \text{ mm}^2$. These difficulties are solved in the modified version, presented in this paper, in the following way :

- a) The laser tube is fixed on the plate at its top. It means that the laser source is found on the same side of the test section.
- b) Two plane mirrors, of the same optical quality as the other mirrors of the system, are mounted on an arm to reflect the laser beam twice passing through the test section of the cryogenic wind tunnel and perpendicular to its axis.
- c) A diaphragm 3 mm of diameter is added after the second, to limit the diameter of the laser beam just before crossing the measuring section.
- c) Dimensions of the ellipse are enlarged such that the measuring room may reach $150 \times 300 \text{ mm}^2$.

The major advantage of the modified laser system is that once it is adjusted it could be used several times without urgent need to be readjusted. Moreover, on sliding this system on smooth and fine rails evolution of size-distribution of particles along the axis of the test section of the cryogenic wind tunnel could be determined .

ANALYSIS OF RESULTS

Size-distribution functions (in number and volume) of particles of liquid nitrogen carried in the airstream of a pilot cryogenic wind tunnel are investigated experimentally by means of the modified laser system presented in this paper. Figure 4 presents a sample of results. It is evident that the number of fine particles is higher than gross ones. In general, these results are in accordance with known distribution functions. It is't shown here any comparison with theoretical distributions because it

is beyond the aim of this paper. The main objective of the present paper is the modification of the laser system and its advantages in the area of determining size-distribution of particles by scattered light detection.

CONCLUSION

The modified version of the laser system presented in this paper is convenient to be used in determining size-distribution of particles , their volumetric concentration and mean diameters. This system could be shifted smoothly, during measurements, to investigate evolution of size-distribution along the axis of the test section . Once it has been adjusted there is no need to further adjustments. This device could be used in the following areas: cryogenic wind tunnels, aerosols , combustion and in two-phase-flow (liquid - gas) generally.

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Fig.1 Schematic of modified laser system

Fig.2 Schematic of initial laser system

Fig.3 Scattering pattern diagram