DESIGN AND COMMISSIONING OF A LASER DOPPLER VELOCIMETRY SEEDING SYSTEM FOR NON-IDEAL FLUID FLOWS

Gallarini S.[1], Spinelli A.[1], Cozzi F.[1] and Guardone A.[2]

[1]Energy Department
[2]Aerospace Science and Technology Department
Politecnico di Milano
Milano, 20156
Italy
E-mail: simone.gallarini@mail.polimi.it

ABSTRACT

The design, the construction and the commissioning of a seeding system for Laser Doppler Velocimetry operating in non-ideal conditions, namely in the close proximity of the liquid-vapor saturation curve and critical point, is presented. The system is implemented in the Test Rig for Organic VApors (TROVA), a facility built at CREALab (Politecnico di Milano) with the aim of characterizing non-ideal gas flows representative of those occurring in Organic Rankine Cycle turbine passages. The tested fluid is the siloxane MDM (Octamethyltrisiloxane – $C_8H_{24}O_2Si_3$), a silicon oil of particular interest for high temperature ORC applications.

Depending on the test operating conditions, the fluid under scrutiny expands in a convergent-divergent nozzle from total pressure and total temperature ranging from 4 bar to 25 bar and from 253.2 °C to 310.3 °C respectively, therefore the seeding has to be injected in a high temperature and high pressure environment, without altering the thermo-fluid dynamic behavior of the fluid. A suspension of the tracer particles (titanium dioxide, TiO_2 or silicon dioxide, SiO_2) in the working fluid is atomized into the flow, in a plenum ahead of the nozzle inlet. Since the surrounding fluid is in superheated vapor (or supercritical) conditions, the spray then evaporates leaving the solid particles free to follow the flow. The designed system consists of a tank, pressurized with nitrogen and containing the MDM-seeding suspension, of a jet mixing system, to maintain the suspension stirred, and of a drawing line ending with the atomizing nozzle. During normal operation, the tank is pressurized at a pressure higher than the plenum one and the fluid flows naturally through the atomizer.

The system has been commissioned and validated through the verification of its operation. The system is suitable for all cases where optical measurements (LDV, PIV, etc.) have to be applied in high temperature, high pressure conditions similar to those occurring in the TROVA and whenever the use of auxiliary fluids different from the working one is not feasible. The reported test proves the suitability of the system in properly seeding the flow.

NOMENCLATURE

p	[bar]	Pressure
T	[K, °C]	Temperature
Z	[-]	Compressibility factor
$\dot{V}$	[m^3/s]	Volumetric flow rate
V	[m^3]	Volume
f	[Hz]	Frequency
St	[-]	Stokes number
v	[m/s]	Particle velocity
u	[m/s]	Flow velocity
d	[m]	Diameter
$\bar{n}$	[m^{-3}]	Particle mean concentration
s	[-]	Relative slip velocity of particles
m	[kg]	Mass
$\dot{m}$	[kg/s]	Mass flow rate
M	[-]	Particle mass concentration in the suspension
F	[m]	Focal length of the LDV optics
λ	[µm]	Laser beam wavelength
ε	[-]	Expansion ratio of the LDV optic
VS#	[-]	Valve number #
PS#	[-]	Pressure transmitter number #
PSD#	[-]	Differential pressure transmitter number #

Special characters

ρ	[kg/m^3]	Density
ζ	[-]	Particle to fluid density ratio
Θ	[s]	Characteristic time
τ	[s]	Response time
μ	[Pa s]	Dynamic viscosity
θ	[°]	Incidence angle of laser beams

Subscripts

c	Critical
Tn	Total condition at the nozzle
inj	Injected quantity
$c-o$	Cut-off
0	Initial value
p	Particle quantity
f	Fluid quantity
m	Measurement, referred to the measurement volume
w	Beam waste quantity

INTRODUCTION

The interest in non-ideal fluid dynamics has grown in recent years, due to the variety of fields where such flows are encountered. Thermodynamic models for non ideal fluids are currently embedded in simulation codes and their use is relatively straightforward. However, experimental results validating non-ideal thermodynamic models are still lacking in literature.

The industrial interest in non-ideal flows, includes different applications. Among these, Organic Rankine Cycles (ORC) gained a relevant role in power production from low to medium temperature sources and for low to medium power applications, especially when a high reliability is required. They are usually preferred over the steam cycle for their low cost, plant simplicity and good thermodynamic efficiency ([1], [2] and [3]). The turbine efficiency plays a relevant role in the plant thermodynamic efficiency, but it is now limited to values of about $80-85\%$ [4], since the turbine expansion occurs mainly in the dense gas region (near the saturation curve in the vicinity of the critical point). The fluids usually employed in ORCs feature high complexity and molecular weight, thus the resulting flows are highly supersonic and real gas effects are not negligible.

In order to provide accurate measurements for the validation of non-ideal thermodynamic models, a wind tunnel called Test Rig for Organic VApors (TROVA) has been constructed at CREALab (Politecnico di Milano). To fully characterize the thermo-fluid dynamics of the expanding flow, independent measurements of temperature, pressure and velocity are required. A direct velocity measurement is required, due to the lack of non-ideal gas calibration wind tunnels for pressure probes. To this purpose optical techniques are preferred and, in the considered application, Laser Doppler Velocimetry (LDV) was chosen. The tested fluid is the siloxane MDM (Octamethyltrisiloxane – $C_8H_{24}O_2Si_3$), a silicon oil of particular interest for high temperature ORC applications. The fluid exhibits a relatively low critical pressure, $p_c = 14.15$ bar, and a high critical temperature, $T_c = 290.94\,°C$.

For gas flow seeding, on the basis of the characteristics (temperature, pressure and other constraints) of the flow to be inseminated, either solid or liquid particles could be used. Among liquid particle generation methods there is the condensation of a saturated vapor [5]. Monodispersed aerosol generators are commercially available [6]. Sometimes, fog generators are used. Another liquid droplet generation method is by atomization. Common types of atomizers are the air-assist ones (such as the Larskin atomizer [7]), also called twin fluid atomizers, and those exploiting the Rayleigh instability of a jet. To generate solid particles, a powder can be dispersed in a liquid and then atomized through a nozzle. The liquid then evaporates leaving solid particles tracing the flow. Another common way is to introduce directly the powder in a gas stream, without the help of a liquid. Some examples of these systems are the rotary brush seeder, the cyclone aerosol generator and the fluidized bed [8]. Regarding high temperature applications, in [9] a fluidized bed is used for PIV measurements in reacting flows.

The seeding in the TROVA plant is not straightforward: the flow to be inseminated is at high temperature (between 253.2 °C to 310.3 °C) and at high pressure (4 bar to 25 bar). Liquid droplet seeding cannot be used, since droplets tend to evaporate and contaminate the fluid under test. Furthermore, along the expansion the pressure varies considerably, leading to a large variation in surface tension, thus in particle dimension. Concerning solid particles, the rotary brush seeder is not applicable due to the need of using MDM vapor at high temperature and pressure to drag the particles. These requirements greatly complicate the design of the system, which has been, therefore, rejected. Cyclone aerosol generator and fluidized bed systems were also discarded due to vapor condensation issue and pressure and temperature constraints.

Table 1. Operating conditions for the MDM tests at the TROVA.

Test	p_{Tn} [bar]	T_{Tn} [°C]	Z_{Tn}
MDM_1	25	310.3	0.31
MDM_2	10	276.9	0.62
MDM_{1st}	4	253.15	0.86

The absence of a system for seeding of high pressure and temperature flows led to the design of a completely new system, based on the atomization of a liquid suspension of MDM and the seeding powder.

In the present paper the TROVA plant is briefly presented, including the working fluid, the thermodynamic cycle, the working conditions and the test section. Then the design constraints for the seeding system are reported. The final layout is discussed and tests and results are presented in the last section.

THE TROVA PLANT

The aim of the TROVA facility is to study the behavior of expanding non-ideal vapors. The plant is a blow down wind tunnel based on a ORC cycle, where the turbine is replaced by a converging-diverging nozzle. Linear turbine cascade can be also tested. The fluid selected for the experiments (the siloxane MDM) is widely diffused for high and medium temperature ORC applications. As previously mentioned, the properties to be measured are temperature, pressure and velocity, in particular the inlet total pressure, the inlet total temperature, the velocity and the static pressure along the axis of the nozzle. The tests to be performed are representative of the working conditions of present and possibly future ORC turbines and are reported in table 1.

Since the plant is a batch system, the fluid undergoes the following processes [10] (figure 1): the required amount of fluid is stored in a closed volume (a tank) and heated up to superheated or supercritical conditions ($2 \rightarrow 4$). The tank pressure is higher than the nozzle stagnation one. The pressure is then regulated through a control valve to a constant stagnation pressure into the plenum ($4 \rightarrow 6$), where total pressure p_{Tn} and temperature T_{Tn} of the nozzle are measured. The fluid then expands through a planar nozzle ($6 \rightarrow 7$), where static pressure on the axis are measured. The test section has an optical access to perform LDV measurements and Schlieren visualizations of the flow field. The planar nozzle has been designed through a standard method of characteristics modified for dense gases (see [11]). The fluid is then discharged into a low pressure vessel, where it is condensed

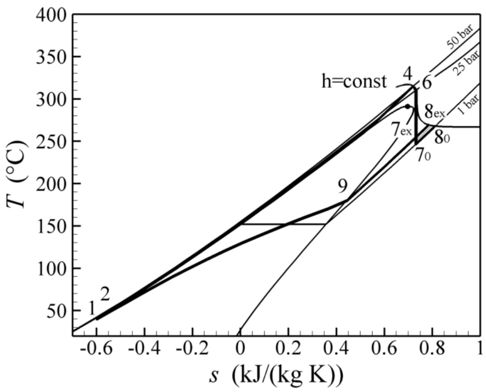

Figure 1. The thermodynamic cycle implemented on the TROVA.

($7_0 \rightarrow 1$). The circuit is then completed by a metering pump that compresses the fluid to the initial high pressure tank ($1 \rightarrow 2$).

PRELIMINARY DESIGN CONSTRAINTS

Particle dynamics

As previously mentioned, the flow to be inseminated is at high temperature and pressure, thus solid particles have to be used. Particles have to exhibit a good refractive index n and a particle density ρ_p and diameter d_p suitable for an adequate tracking of the flow.

As shown in [12], when the particle to fluid density ratio $\zeta = \rho_p/\rho_f = 1$, the energy is transferred properly from the flow to the particle throughout all the Stokes number $St = \tau_p/\Theta_f$ range, where τ_p is the response time of the particle and Θ_f is the characteristic time of the flow. So an ideal seeding material would have a density similar to the fluid one: $\rho_p \approx \rho_f$. The particle dimension is a compromise between the need of a small particle to properly follow the flow and large particles to scatter more light, to improve the signal quality.

Since the Stokes number St compares the response time of the particle with the characteristic time of the flow, $St \ll 1$ is required. More in detail, in [12] correlations are reported that give the Stokes number St resulting in a particle velocity v between $\sqrt{0.5}$ and $\sqrt{2}$ times the flow velocity u. From the Stokes number St is then possible to obtain the cut-off frequency f_{c-o} that could be tracked, with the fixed constraints between particle and fluid velocity. In the TROVA application, there is no need to fully resolve the turbulence, therefore the required dimension has to permit only an accurate tracking of the flow along the nozzle axis.

The motion of a particle in a turbulent flow is described by the Basset – Boussinesq – Oseen equation, valid for spherical particles, negligible particle-particle interaction, homogeneous velocity profile over the particle and Reynolds number $Re = \rho d_p |u-v|/\mu = 0$. In the considered application, by setting a slip factor $s = (u-v)/u = 0.01$ and using data from CFD calculations, particle Reynolds number lies in the range $0.4 \div 4.5$. A common approach when dealing with finite particle Reynolds numbers is to simplify the equation of motion, that, for an horizontal trajectory, becomes

Table 2. Maximum slip factors s for different particle diameters and material.

Test	TiO_2		SiO_2	
	$d_p = 1\,\mu m$	$d_p = 0.5\,\mu m$	$d_p = 1\,\mu m$	$d_p = 0.5\,\mu m$
MDM_2	5.57%	2.35%	4.06	1.61%
MDM_{1st}	3.86%	1.36%	2.70	0.90%

$$\frac{\pi}{6} d_p^3 \rho_p \frac{dv}{dt} = -3\pi\mu d_p (v-u)\phi, \tag{1}$$

where the term on the right hand side of equation (1) is the quasi-steady Stokes term modified with the ϕ coefficient to account for the deviation in the Stokes drag when the particle Reynolds number is not zero. A simple relation for the ϕ coefficient is $\phi = 1 + 0.15 Re_p^{0.687}$ [13].

A numerical integration of equation (1), for a trajectory coincident with the nozzle axis, was performed, with a slip factor $s = 0.01$ at the nozzle inlet, for different particle diameters, and the results are reported in table 2 (a CFD simulation is not available for the test MDM_1, thus only tests MDM_2 and MDM_{1st} are reported). It is evident that particle diameter d_p less than $0.5\,\mu m$ should be chosen.

The particle should reach the flow velocity at the nozzle inlet, from the velocity at which it is inseminated. As an index of the particle dynamic behavior, the particle response to a step with an amplitude equal to the nozzle inlet fluid velocity can be considered. The solution of the particle velocity through the step is an exponential function and, if a slip factor $s \leq 1\%$ is required, the particle needs a distance $4.6\tau_p u$ to reach the fixed velocity, where τ_p is the response time given by

$$\tau_p = \frac{d_p^2 \rho_p}{18\mu}\left(1 + \frac{1}{2}\frac{\rho_f}{\rho_p}\right). \tag{2}$$

Particle concentration

The mean concentration of particles in the flow should be kept sufficiently low to avoid multiple particles in the measurement volume and sufficiently high to have a satisfying data rate. If the particle concentration is chosen so that

$$\bar{n}_p \leq \frac{0.1}{V_m}, \tag{3}$$

the probability to have two or more particle in the measurement volume is less than 0.5% [8]. V_m is the measurement volume and, by assuming it is an ellipsoid, it can be obtained as a function of the focal length of the LDV optics F, the expansion ratio ε, the

Table 3. Properties of TiO_2 and SiO_2.

	TiO_2	SiO_2
Particle density [kg/m^3]	$3900-4200$	2200
Melting point [°C]	1830	1700
Primer particle [nm]	20	12
Cluster particle [nm]	$150-250$	$100-150$

beam diameter before expansion d_w, the laser wavelength λ and the angle between laser beams θ:

$$V_m = \frac{64}{3} \frac{(F\lambda/\varepsilon d_w)^3}{\pi^2 \sin\theta}. \quad (4)$$

To achieve a higher data rate it is necessary to take the particle concentration $\bar{n}_p$ equal to $\bar{n}_p = \frac{0.1}{V_m}$. Knowing the volumetric flow rate at each section of the nozzle, the particle flow rate can be determined for any measurement point along the axis.

From these quantities, it is possible to determine the volume flow rates $\dot{V}_{inj}$ required and the total volume to be injected V_{inj} for a single test and a single measurement point, which depend on the particle loading $M = m_p/m_f$ of the suspension, that is a degree of freedom in the design of the system.

Selected seeding particles

With these constraints in mind, two different seeding powders have been selected, whose characteristic are reported in table 3. As it can be noted, trackers have a density much higher than the vapor one, since they are solid metal oxydes. This tends to result in a poor tracking, thus requiring smaller particles than in other cases. In fact, cluster particles are quite small. The melting temperature is high, and this is compatible with the temperature found in the TROVA.

The aforementioned analysis yields a cut-off frequency f_{c-o} ranging approximately between 10^5 Hz and 3.2×10^5 Hz, which is quite high, for the considered application. The response time τ_p relative to a particle accelerating from 0 m/s to fluid velocity ranges from 7.3×10^{-7} s to 1.6×10^{-6} s. Since the fluid velocity u in the plenum, where particles are injected, is of the order of 1 m/s, the distance to have a slip factor $s = 1\%$ is $4.6\tau_p u = 7.4 \times 10^{-7} \div 3.4 \times 10^{-6}$ m, far below the distance between the injection point and the test section. Furthermore, the particle is injected with a velocity $v_0 \neq 0$, so the needed distance is even lower. By fixing a representative particle diameter $d_p = 250$ nm, the suspension particle loading can be selected to obtain the volumetric flow rate $\dot{V}$ and the volume V. With a particle concentration M in the range from $5 \cdot 10^{-5}$ to 10^{-7}, volumetric flow rates $\dot{V}$ between 50 ml/min and 300 ml/min and injected volume V from 50 ml to 300 ml are obtained.

SYSTEM LAYOUT

According to the presented constraints, the system represented in figure 2 has been designed. It is composed by a tank, a pressurizing system, a level meter, a mixing system and an atomizer.

The tank is partially filled by a suspension of MDM and the seeding particles and has a volume $V \approx 3.5\,l$. It is pressurized with nitrogen through the pressurizing system. During a test, the tank is maintained at a pressure higher than the injection point one (within the plenum), therefore, when the valve VS3 is opened, the suspension naturally flows through the spraying nozzle line, following the law $\dot{m} = C_d A \sqrt{2\rho\Delta p}$, where C_d is the discharge coefficient and A is the area of the nozzle orifice. The flow rate depends on the pressure difference Δp applied to the atomizer, which is finely regulated by the metering valve VS2 and and controlled by the pressure meter PS1. The nozzle is an hydraulic atomizer that exploits the Rayleigh instability: since assisting fluids are not used, the tested fluid is not contaminated. The pressurizing system consists of a nitrogen reservoir at 200 bar with a pressure regulator and a transmitter PS4 to monitor the regulated pressure.

Solid particles in suspension tend to sediment, therefore a mixing circuit draws the suspension from the tank and recirculates it through a pump and a mixing nozzle. The nozzle creates an axial jet impinging on the lower cap of the tank at a velocity $u_{jet} \approx 10-15$ m/s. The mixing system has been designed following the guidelines in [14] and [15]. This system is designed also to fill the tank with the suspension and to clean all the lines with pure MDM.

The level measurement system consists of a visual level indicator and a differential pressure transmitter, which gives the level by measuring the pressure difference between the lower liquid part of the tank and the nitrogen side.

The system is protected from overpressure by a rupture disk sized for a bursting pressure of 50 bar. The discharge line is connected with the TROVA relief valve discharge pipe. Since the system could work either in subcritical or supercritical conditions, the sizing of a relief valve presented uncertainties, because of the extreme variation in possible thermodynamic conditions of the fluid at the opening point. Finally a burst diaphragm was chosen, sufficiently oversized to discharge all the needed mass in case of opening.

SYSTEM VALIDATION AND RESULTS

Currently, the system is constructed and under test. The most important aspects to be tested, for LDV measurements, are connected with the atomization: the atomization process itself has to be tested with MDM, an experimental curve giving the pressure difference Δp on the atomizer as a function of the atomized flow rate $\dot{V}$ has to be obtained and the droplet evaporation before the the test section has to be assessed. The first two tests are necessary, since data are only available for the nozzle operation with water.

$\Delta p - \dot{V}$ curve

The pressure–volumetric flow rate $\Delta p - \dot{V}$ curve can be obtained by filling the tank with MDM, pressurizing it at different pressure values and letting discharge the resulting flow rate through the atomizer. The pressure difference on the nozzle is

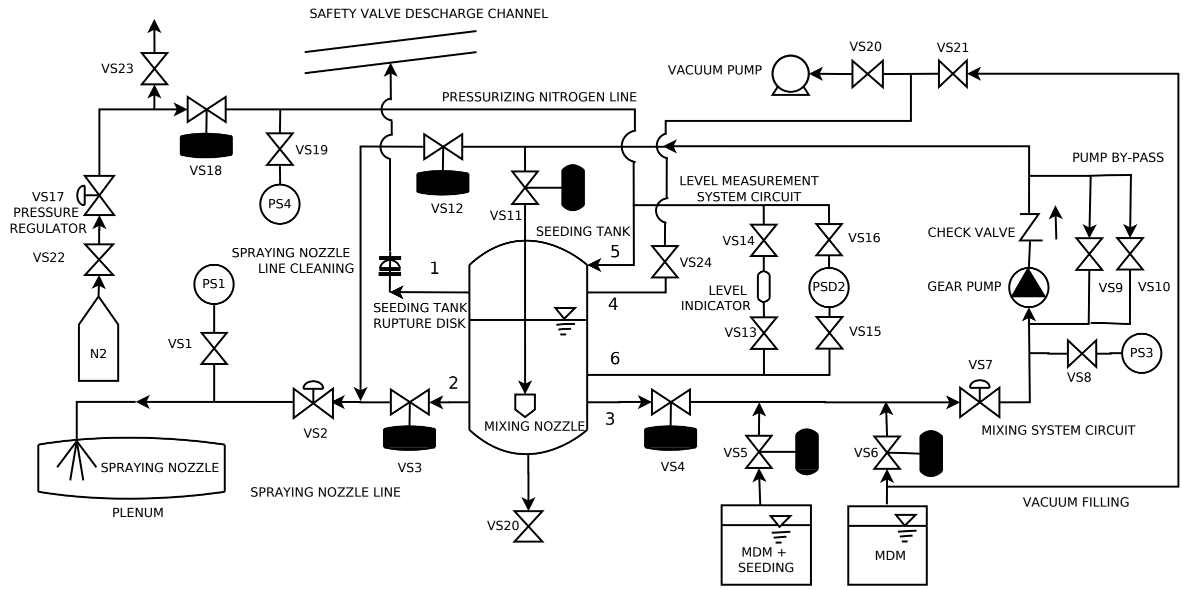

Figure 2. Sketch of the designed seeding system.

Figure 3. Picture of the spray generated by the atomizer.

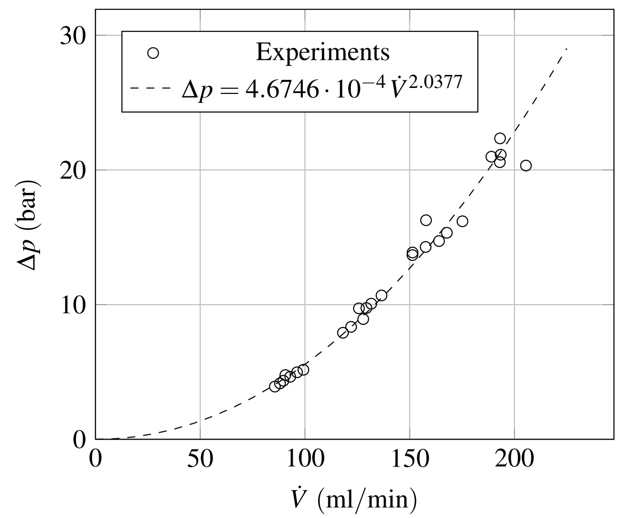

Figure 4. Pressure difference Δp imposed on the nozzle as a function of the volumetric flow rate $\dot{V}$.

monitored by PS1. The flow rate is obtained from the level measurement of the liquid in the tank over time. In figure 4 is reported the pressure difference Δp imposed on the nozzle as a function of the volumetric flow rate $\dot{V}$. The pressure difference on the nozzle Δp can be expressed as

$$\Delta p = \frac{\rho}{2}\left(\frac{\dot{V}}{C_d A}\right)^2. \quad (5)$$

By fitting the experimental data with a curve $\Delta p = K\dot{V}^{\alpha}$ (Δp in bar and $\dot{V}$ in ml/min), $K = 4.7646 \cdot 10^{-4}$ and $\alpha = 2.0377$ are obtained (see figure 4). In figure 3 is reported a picture of the spray, for atomization in ambient air.

Droplet evaporation

To assess that the designed system operates as expected, two different tests were performed on the TROVA:

A velocity measurement at a point of the nozzle axis without seeding the flow. This is the reference case used for comparison with other tests;

B velocity measurement at a point of the nozzle axis, spraying pure MDM. This test is useful to assess if complete evaporation is achieved.

In Test A, no measurements are expected, being the flow free of any seeding particle. However, some impurities may be present in the flow and could be detected by the system electronics. If some measurements are made in this configuration, test B must be compared to the result of this test, to make any conclusion. During Tests A, no measurements were obtained. In figure 5 are reported velocity measurements for the test B. The test starts

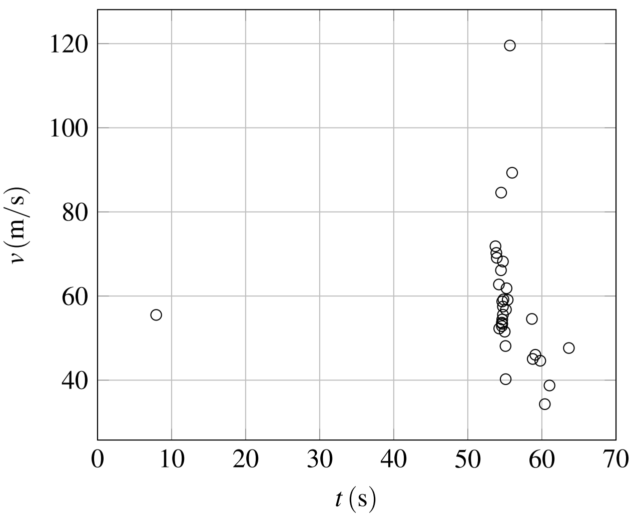

Figure 5. Velocity measurements for the Test B.

at $t = 8$ s and concludes at $t = 53$ s. A set of measurements at the beginning and at the end of the test, with velocity values far from the expected ones, is present (figure 5). At the test start, a transient period is present, where the atomization process is inefficient (due to the low Δp on the atomizer), thus resulting in large injected droplets. The same happens at the end of the test. This results in a set of large, partially non evaporated droplets that are detected by the LDV system. Therefore, except for the initial and final transients, the evaporation is complete.

CONCLUSION

A Laser Doppler Velocimetry seeding system for non-ideal flows has been designed and tested. The system has to allow the performance of LDV measurements on the Test Rig for Organic VApors for the characterization of the flow field in real gas expansions. The high temperature and pressure, the nature of the working fluid and the purpose of the application led to a set of constraints that have been respected. The atomization process has been tested and the characteristic curve of the atomizing system has been obtained. Furthermore, the droplet evaporation has been analyzed, leading to the conclusion that complete evaporation is reached. The system is constructed and further tests are currently under way, bringing to the first LDV measurement in a MDM supersonic expansion flow field.

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