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TAKING-OFF UNDER TROPICAL STORM : A NEW STEAM AND WATER INJECTION FEATURE IN THE K9 COMBUSTION TEST RIG OF DGA AERO-ENGINE TESTING

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ABSTRACT

The K9 combustion test facility enables characterization of combustors at sea level with a new steam injection feature to simulate ingestion of rain and hail by the combustor. By providing steam and water directly to the combustor, DGA is now able to check its stability and its loss of efficiency under the most severe test conditions. In this paper, the description of this new water supply will be made and a brief description of quality of the spray used for the production of steam will be presented. A specific study has been made concerning the air flow measurement with some corrections due to the presence of high concentration of steam in the air. The second part of this paper is dedicated to the control of the vaporization of water, the correct control of the steam / air ratio in the flow and the consequences on the thermal behavior of the facility.

INTRODUCTION

Regarding the importance of water ingestion for engines certification [1] and in order to provide up-to-date facilities to its partners and customers, DGA invests by extending its combustion capabilities (Table 1). That's why a new steam and water injection system has been developed for the K9 in order to provide controlled Water Air Ratio to the combustor. Document [2] and [3] clearly mention the certification standard atmospheric concentration of rain and hail. From these information the manufacturer can deduce the test conditions required for its engine and consequently those required by the combustor in order to study and anticipate the risks of flameout. To simulate rain ingestion implies a precise control of the Water Air Ratio (WAR) inside the air flow. The condensation of steam is another issue in this kind of test and DGA has checked the efficiency of steam production and demonstrated its reliability. Injecting water and producing steam has also a great impact on the thermal behavior of the test rig itself. Consequently, reaching the correct Water Air Ratio with the right inlet temperature for the test unit is a challenge for such industrial facility. This paper will present the different steps of the development of this new feature and its validation during real test conditions.

Combustion test rig	Air flow	Inlet pressure	Inlet temperature
A06	4,2 kg/s	0,2 to 1,2 bar	- 45 to 100 °C
K8	23 kg/s	23 bar	520 °C
K9	12 kg/s	1 bar	520 °C
K11	100 kg/s	60 bar	800 °C

Table 1 – Main characteristics of combustion test rigs at DGA.

WATER SUPPLY

On the K9 facility, three different demineralized water supplies can be used for the test of rain ingestion. Two lines are dedicated to the test unit itself in order to supply liquid water at ambient temperature (Fig. 1). The spray of water inside the

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specimen can be produced with various devices (injector, long slotted hole, etc…) and DGA provides demineralized water flow with a maximum pressure of 5 bar and a maximum flow of 700 l/h per line. The third line is used to produce steam in the air flow with a dedicated injection device. The flow rates are supplied by hydraulic pump and rare measured with turbine flow meters which allow the control of the required water flow rate with accuracy better than 1%.

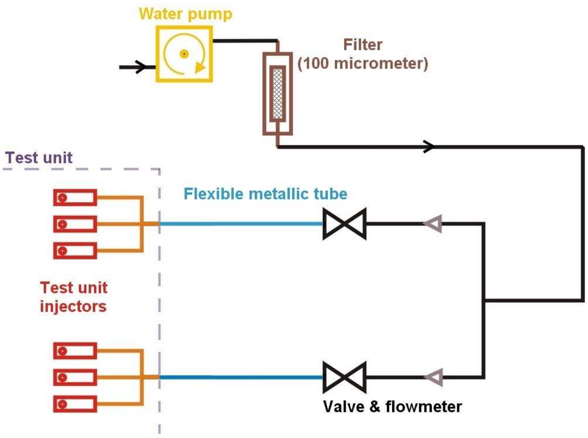

Figure 1 – Scheme of the liquid water supply

STEAM INJECTOR CHARACTERIZATION

The steam production inside the pipes of K9 is made with a pneumatic injector where water is sprayed by pressurized air (Fig. 2). The capabilities of this injector are 50 – 650 l/h with a stabilized behavior between 100 and 600 l/h. The droplet size distribution of the steam injector has been assessed at ambient pressure and temperature in order to check the quality of the water spray. The drop size distribution of the spray has been roughly measured with a cloud droplet probe and is given on Fig. 3 for a flow of 400 l/h. The different drops diameters D_{10}, D_{20}, D_{30}, D_{32} are summarized in table 2.

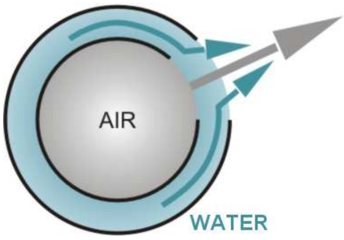

Fig. 2 – Water injector (cut plane).

D_{10}	D_{20}	D_{30}	D_{32}
~ 120 µm	~ 130 µm	~ 150 µm	~ 180 µm

Table 2 – Droplets diameters for a flow of 400 l/h.

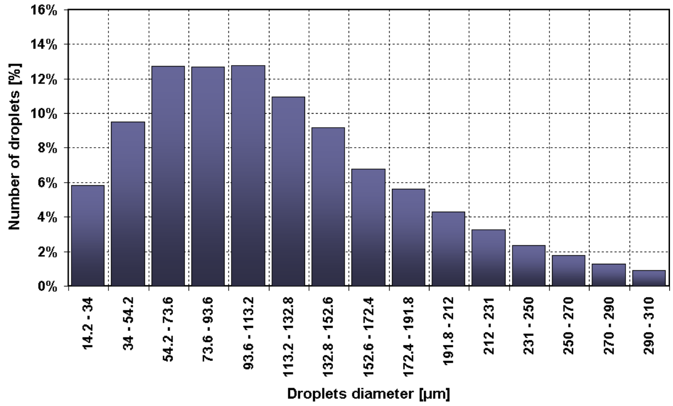

Figure 3 – Droplet size distribution of the steam injector spray.

MOIST AIR FLOW MEASURMENTS

Air flow measurements on K9 facility are made with a orifice and according the ISO Standard [4, 5]. In these references, only dry air is considered. So, due to the presence of a high quantity of steam inside the air flow during water ingestion tests, DGA had to adapt this method. The molecular weight of dry air is usually equal to 0.028966 kg.mol^{-1}. The water / air mixture has a molecular weight of:

$$M_{wa} = \frac{M_w \cdot M_a \cdot (1+r)}{M_w + M_a \cdot r}$$

The specific heat capacity at constant pressure follows a simple mass fraction law where r is the ratio between the mass of water and the mass of dry air.

$$c_{P,wa} = \frac{c_{P,a} + r \cdot c_{P,w}}{1+r}$$

The specific heat capacity of steam is deduced from data of the International Association for Properties of Water and Steam (www.iapws.org). The specific heat capacity of dry air is given by [6].

$$c_{P,w} = -1.9184 \cdot 10^{-10} \cdot T^5 + 6.0543 \cdot 10^{-7} \cdot T^4 - 7.5888 \cdot 10^{-4} \cdot T^3 + 4.7278 \cdot 10^{-1} \cdot T^2 - 146.02 \cdot T + 19808$$

$$c_{P,a} = 1000 \cdot \left[\begin{array}{l} 0.992313 + 0.236688 \cdot \dfrac{T}{1000} - 1.852148 \cdot \left(\dfrac{T}{1000}\right)^2 \\ + 6.083152 \cdot \left(\dfrac{T}{1000}\right)^3 - 8.893933 \cdot \left(\dfrac{T}{1000}\right)^4 \\ + 7.097112 \left(\dfrac{T}{1000}\right)^5 - 3.234725 \left(\dfrac{T}{1000}\right)^6 \\ + 0.794571 \left(\dfrac{T}{1000}\right)^7 - 0.081873 \left(\dfrac{T}{1000}\right)^8 \end{array} \right]$$

The water / air mixture is considered as a perfect gas.

$$r_{wa} = \frac{r_a + r \cdot r_w}{1 + r} \quad \text{and} \quad \gamma_{wa} = \frac{C_{P,wa}}{C_{P,wa} - r_{wa}}$$

The viscosity of the water / air mixture is modelized by the Wilke's formula [7, 8].

$$\mu_{wa} = \sum_{i=w,a} \frac{\mu_i}{1 + \frac{1}{x_i} \cdot \sum_{\substack{j=w,a \\ j \neq i}} \frac{x_j \cdot \left(1 + \sqrt{\mu_i / \mu_j} \cdot \sqrt[4]{M_j / M_i}\right)^2}{2 \cdot \sqrt{2} \cdot \sqrt{1 + M_i / M_j}}}$$

$$\text{with } x_w = 1 - x_a = \frac{r}{M_w / M_a + r}$$

The viscosity is given by the Sutherland law. Coefficients for dry air come from Fluent database and coefficients for steam come from reference [9].

$$\mu_i = \mu_{i0} \cdot \left(\frac{T}{T_{i0}}\right)^{\frac{3}{2}} \cdot \frac{C_i + T_{i0}}{C_i + T} \text{ with}$$

$$\begin{cases} \mu_{a0} = 1.82 \cdot 10^{-5} \; Pa \cdot s \\ C_{a0} = 113 \, K \\ T_{a0} = 293.15 \, K \end{cases} \qquad \begin{cases} \mu_{w0} = 1.26 \cdot 10^{-5} \; Pa \cdot s \\ C_{w0} = 961 \, K \\ T_{w0} = 373.15 \, K \end{cases}$$

A computation of moist air flow has been made according reference [2, 3] with the hypothesis of dry air and with the DGA modified procedure. The relative difference between the two results has been drawn on Fig. 4 for different flow rate at a temperature of 373 K or 573 K with a pressure of 1 bar. For moderate flow rate, the differences are quite important. The influence of temperature is negligible, that's why curves at 573 K are not shown in Fig. 4.

STEAM PRODUCTION

A scheme of K9 facility is given Fig. 5. Temperature (TT14), static pressure (PS14) and ambient humidity (H14) of air are measured in area 14 of the K9. The water injector used for steam production is located in area 15 and its flow is measured by a turbine flowmeter. There is another air temperature measurement (TTAMONT) before a differential pressure flowmeter (orifice). The temperature of the orifice is also measured in order to estimate its expansion at high temperature (TMDIAPH). Finally, the temperature (TT25), the static pressure (PS25) and the humidity (H25) of moist air are measured in front of the customer's test unit in area 25.

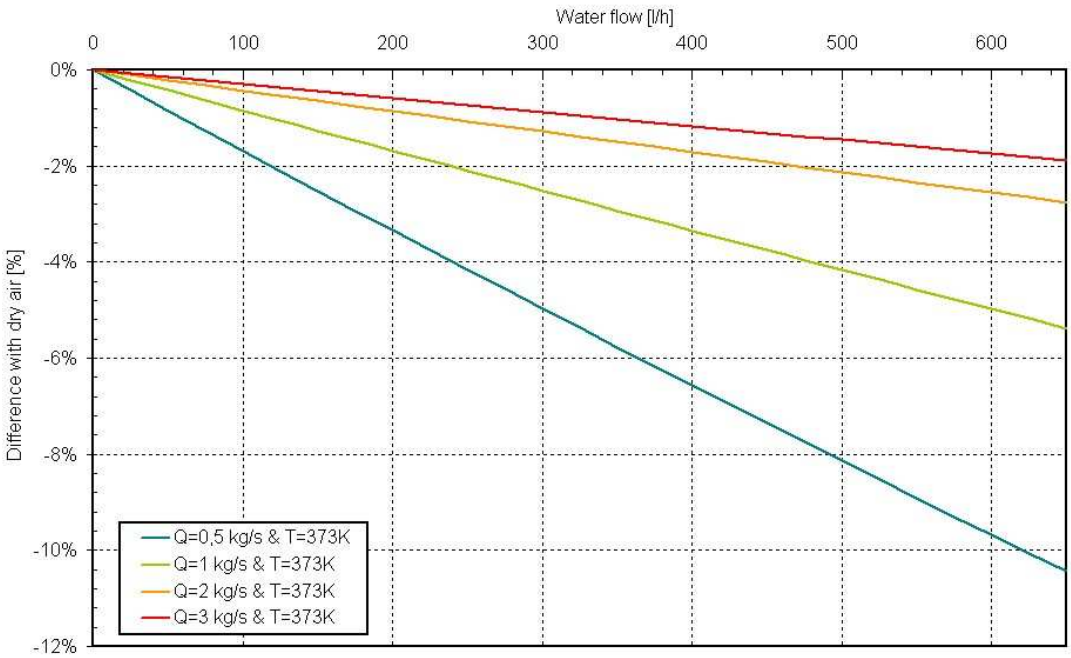

Figure 4 – Relative difference between moist and dry air measurements.

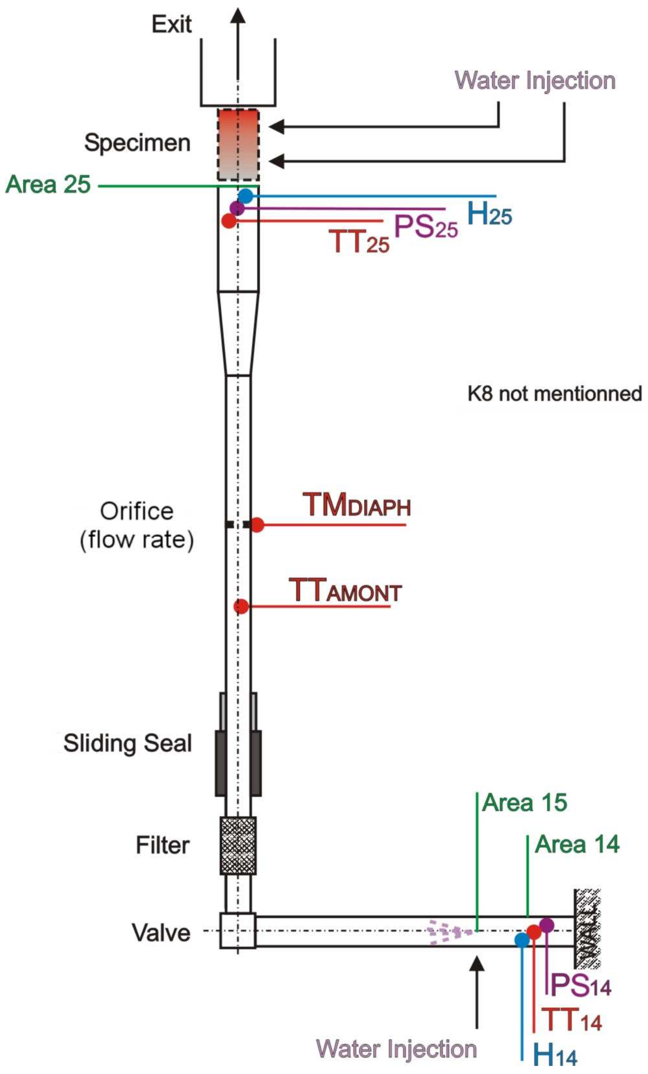

Figure 5 – Scheme of K9 facility and location of measurements

The vaporization of water has been checked with an air flow of 1,5 kg/s. On Fig. 6, the water / air ratios r_{25} and the relative humidity in area 25 are displayed versus time. These parameters come either from the humidity measurement (r_{25} or RH measured) or the flowmeter measurement (r_{25} or RH calc. from turbine). The temperature of air (TT_{25}) and the temperature of dew related to the conditions in area 25 are also displayed.

The water flow is maintained constant (r_{25} calc. from turbine) and the temperature of air TT_{25} decreases slowly in order to verify with a laser sheet not far from area 25 when the condensation of steam happens. Pictures 1 to 4 on Fig. 6 show the gradual transition between different states of the airflow.

When the mixing ration r_{25} measured by the hygrometer and calculated from the turbine are the same (Fig. 6 – picture 1), there is no significant condensation. As soon as these two parameters begin to diverge, some sparks of light can be seen due to the presence of tiny water droplets (Fig. 6 – picture 2). Then, the visualization of liquid water droplets in the air flow becomes more and more obvious (Fig. 6 – picture 3 & 4). So, by comparing the two mixing ratio, we are able to check if all the water injected in area 15 is correctly vaporized in area 25. This test shows us that, even if the temperature of air is greater than the dew temperature, the injected water can't be totally vaporized. Several explanation can be proposed : period of stay between area 15 and area 25 too short, condensation on cold part of the wall, etc... The operating diagram of the steam injection device has been adapted regarding these results.

CONTROLLING THE WATER / AIR RATIO

The water / air ratio r_{25} due to steam which passes through the specimen is controlled by three parameters: flow rate of injected water in area 15, air flow orifice measurements and ambient atmospheric moisture. It is defined as:

$$r_{25} = \frac{\text{flow of water}}{\text{flow of dry air}}$$

$$\begin{cases} \text{Flow rate of water: } Q_{w,25} = Q_{atmospheric\ water} + Q_{injected\ water} \\ \text{Flow rate of moist air: } Q_{w\,a,25} = Q_{dry\ air} + Q_{w,25} \end{cases}$$

$$r_{25} = \frac{r_{14} \cdot Q_{w\,a,25} + Q_{w,15}}{Q_{w\,a,25} - Q_{w,15}} \Leftrightarrow Q_{w,15} = Q_{w\,a,25} \cdot \left(\frac{r_{25} - r_{14}}{1 + r_{25}} \right)$$

As it is said in the chapter WATER SUPPLY, demineralized water can be send directly inside the customer's test unit. The liquid water / air ratio is also easily controlled with flowmeters. Consequently, in area X or Y (Fig. 7), we can write:

$$r_{L,X} = \frac{\text{flow of water from X}}{\text{flow of dry air}}$$

$$r_{L,X} = \frac{Q_{w,X} \cdot (1 + r_{25})}{Q_{w\,a,25}} \Leftrightarrow Q_{w,X} = Q_{w\,a,25} \cdot \left(\frac{r_{L,X}}{1 + r_{25}} \right)$$

$$r_{L,Y} = \frac{\text{flow of water from X} + \text{flow of water from Y}}{\text{flow of dry air}}$$

$$\begin{cases} r_{L,Y} = \dfrac{r_{L,X} \cdot Q_{w\,a,25} + r_{25} \cdot Q_{w,Y} + Q_{w,Y}}{Q_{w\,a,25}} \\ \Leftrightarrow Q_{w,Y} = Q_{w\,a,25} \cdot \left(\dfrac{r_{L,Y} - r_{L,X}}{1 + r_{25}} \right) \end{cases}$$

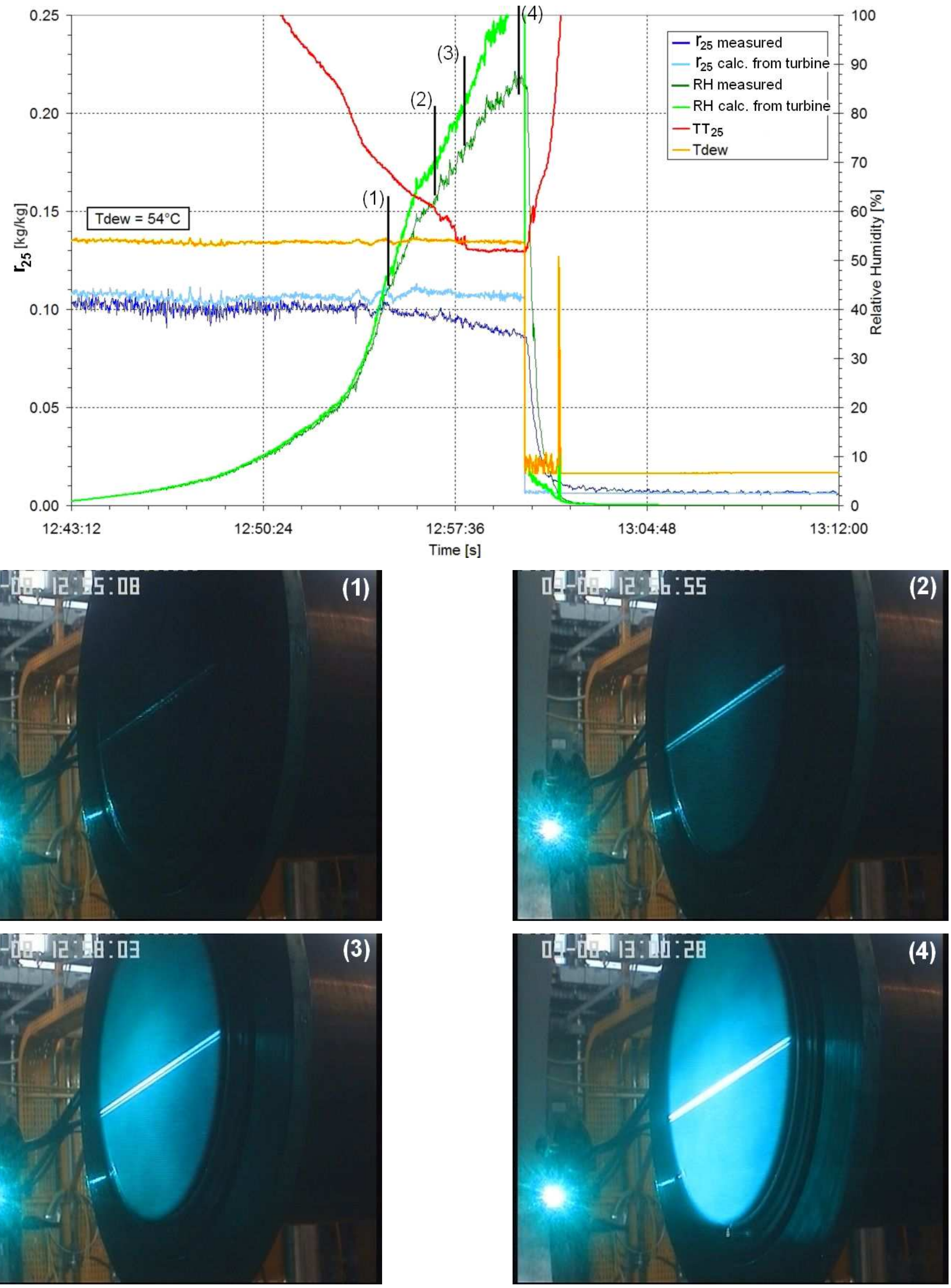

Figure 6 –Visualization of condensation on area 25.

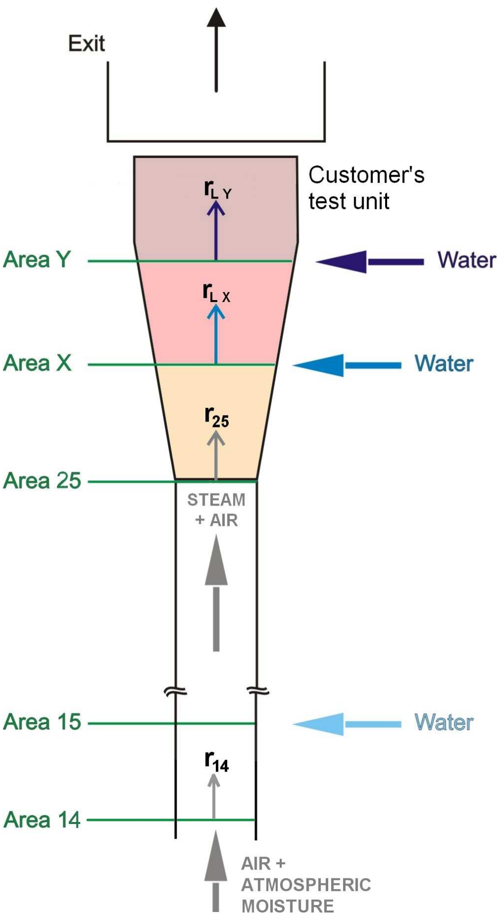

Figure 7 – Description of the different water/air ratio.

STEAM INJECTION OPERATING DIAGRAM

The limited flow of the steam injector and the problem of water condensation in front of the test unit have a great impact on the operating diagram of the K9 steam injection feature. Based on DGA experience, the operating diagram of this steam injection device has been established with the hypothesis of a natural atmospheric mixing ratio of 5g/kg. On Fig. 8, the mixing ratio r_{25} has been plotted versus the temperature of air in area 25 for a pressure of 1 bar. The theorical limit for emergence of dew is mentioned in red. For a given mixing ratio, tests have shown that liquid water appears at higher temperature (orange line). The green area represents the confidence limit where no condensation occurs. The Fig. 9 gives the limit of r_{25} versus the water flow of the injector. These values can be compared with the certification concentration given by document [2]. In the worst case, a maximum level of 20g of water per cubic meter air is asked for an altitude of 20 000 feet and represents a mixing ratio around 30 g/kg. Document [3] shows that, in certain circumstances, an amplification factor of 2.5 can be met during idle descend and led to mixing ratio up to 75 g/kg.

THERMAL SIMULATION OF STEAM INJECTION

Injecting water in area 15 in order to produce steam for area 25 has a great impact on the thermal behavior of the facility. The test unit inlet temperature can substantially vary because of the vaporization of injected water. The temperature of the different structures of K9 (ducts, orifice, filters…) are also impacted by these variations and can have an important influence on the air temperature during transient conditions. The adjustments of test conditions during water injection are such a challenge that a specific tool has been developed in order to modelize the evolution of temperature all day long. This tool is also used to optimize a test day and may have a significant role on productivity. A validation of this tool has been made and is shown on Fig. 10. Input data of the model are air temperature (TT_{14}), flow rate of injected water in area 15, ambient temperature, atmospheric moisture (r_{14}) and air flow rate ($Q_{w\ a,25}$). Output data are: air temperature in area 25 (TT_{25}), orifice temperature (TM_{diaph}). On Fig. 10, input data has been fitted on experimental ones and the results of simulation is then compared with real test data. Some differences appear during the third hour of the tests (red arrow) that probably implies a bad appreciation of the influence of condensation by the software.

CONCLUSION

DGA Aero-engine Testing proven his ability to deliver and control variable quantities of water or steam to the combustor at ambient pressure conditions to study this influence on the flame stability or on the efficiency of the combustion. This feature on K9 facility helps manufacturers to secure their development program regarding the water or hail ingestion.

In the future, the steam injection device should be improved and adapted in order to be used on K8 facility which is located beside K9. The correct vaporization of water inside K8 has to be established without any optical access on the test rig. Fortunately, results of the tests made on K9 have demonstrated the good correlation between the mixing ratio measured by the hygrometer and the one computed from the water turbine measurements. Consequently, optical visualization of the liquid droplets is no more mandatory. Because this test rig works at higher flow rate and higher pressure, some adaptations would be required. The amount of water has to be increased and the pneumatic system of the injector should be completely revised since the pressure inside the K8 duct is slightly higher than in the K9. Some modification on the humidity measurement device on area 14 and 25 has also to be planned in order to deal with the high pressure.

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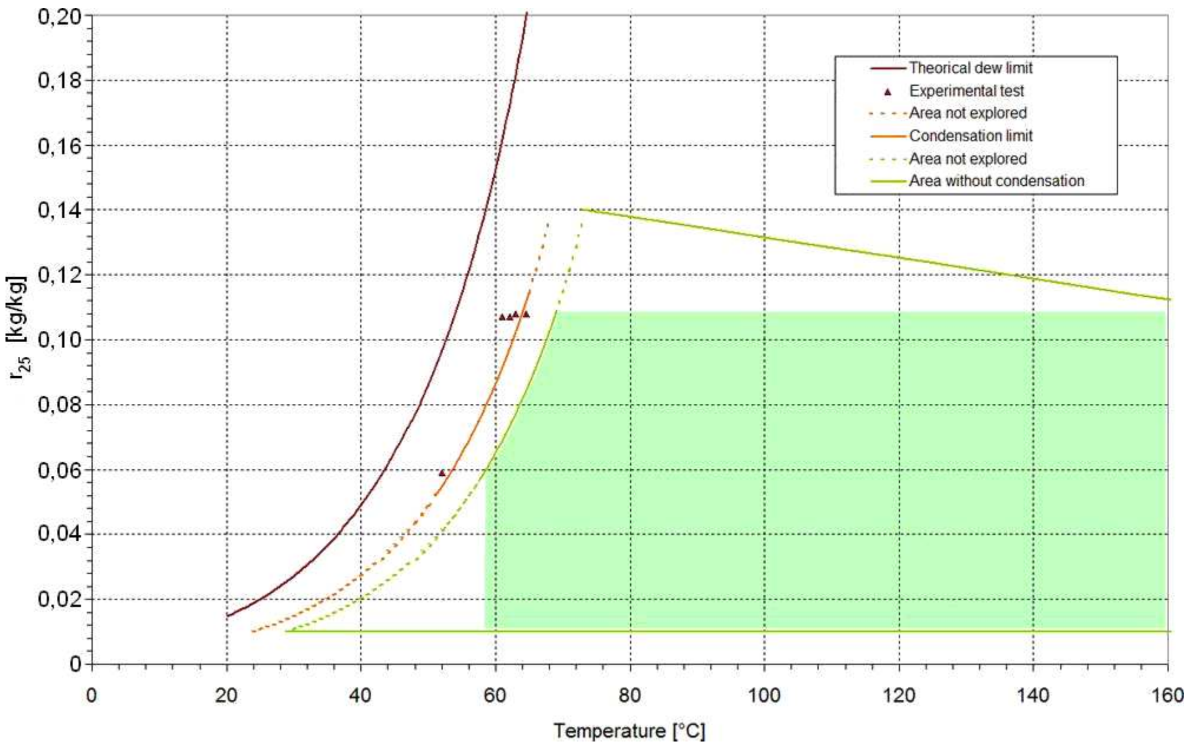

Figure 8 – Operating diagram: mixing ratio versus test unit inlet air temperature.

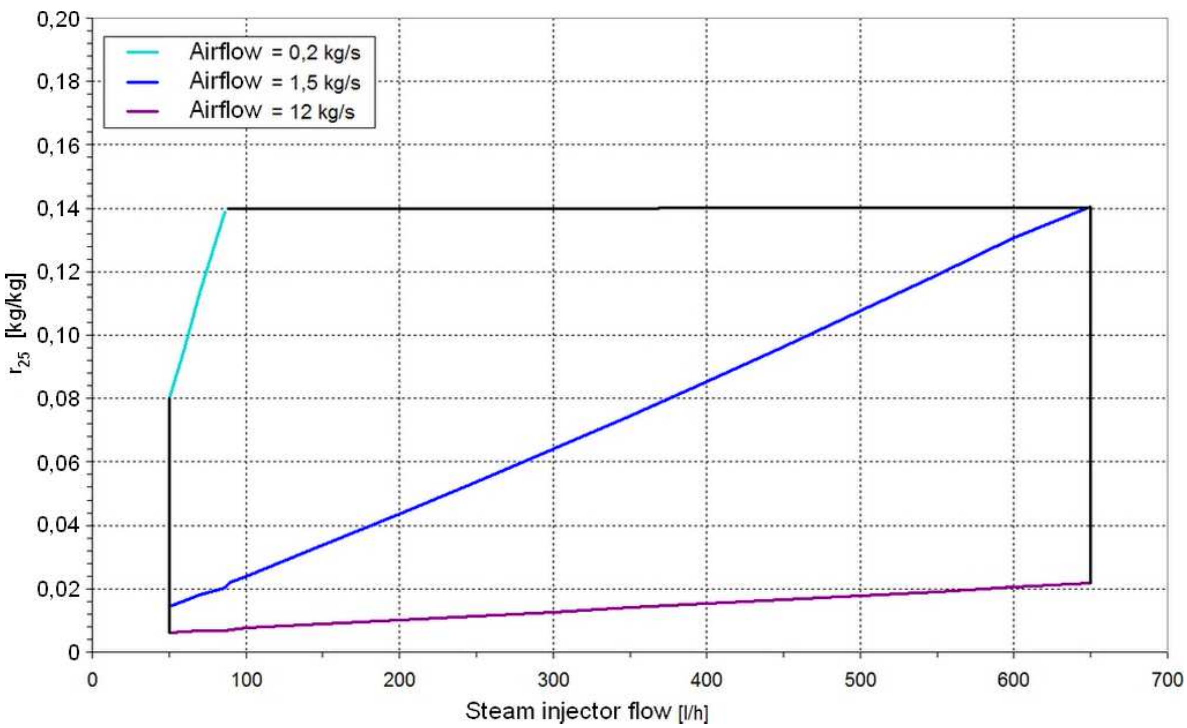

Figure 9 – Operating diagram: mixing ratio versus steam injector flow.

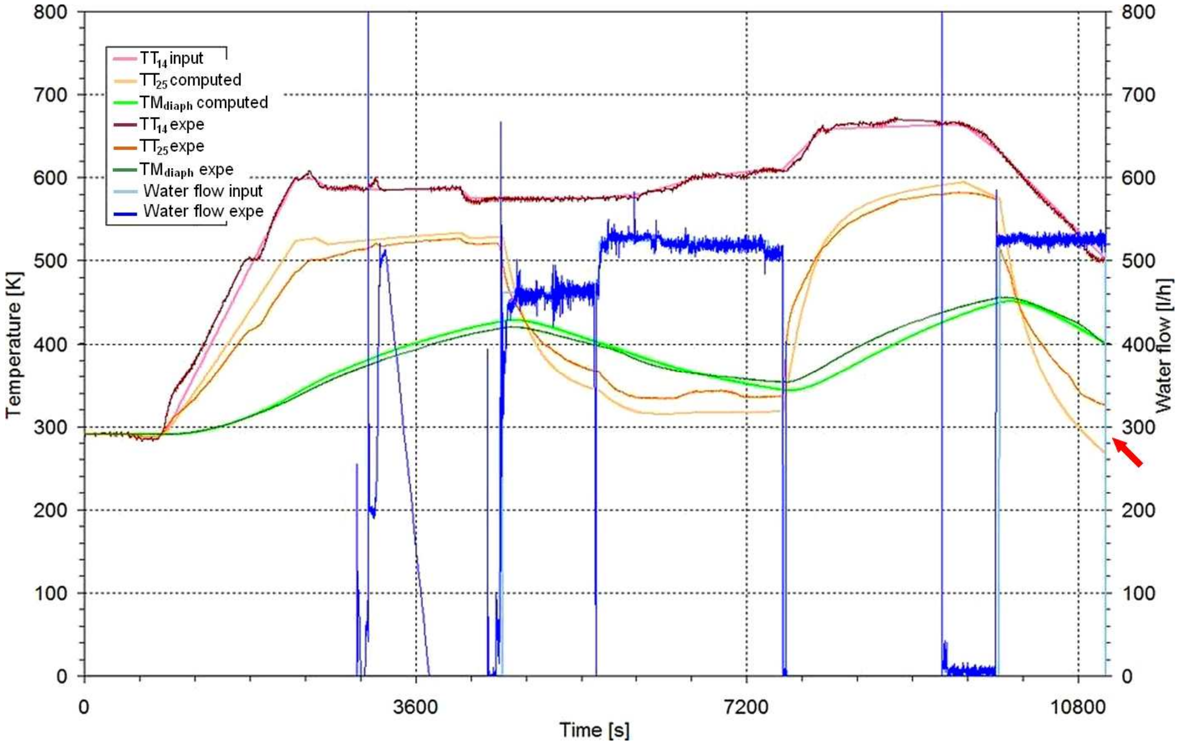

Figure 10 – Validation of the K9 thermal tool.

NOMENCLATURE

Latin letters

c_P = specific heat capacity at constant pressure [J.kg^{-1}.K^{-1}]
C = Sutherland's constant [K]
D = diameter [m]
D_{10} = mean diameter [m]
D_{20} = mean surface diameter [m]
D_{30} = mean volumic diameter [m]
D_{32} = Sauter's diameter [m]
Q = flow rate [kg.s^{-1}]
M = molecular mass [kg.mol^{-1}]
r = mixing ratio [kg water . kg air^{-1}]
r_x = specific gas constant of the gas X [J.kg^{-1}.K^{-1}]
T = temperature [K]
x = molar fraction [-]

Greek letters

γ = heat capacity ratio [-]
μ = dynamic viscosity [Pa.s]

Subscript

14 = related to area 14
15 = related to area 15
25 = related to area 25
a = related to dry air
L = related to liquid water for the mixing ratio r
w = related to water (or steam)
w a = related to water / air mixture

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