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Nonlinear Cascade Fuzzy Control of a Water Droplet Generator in an Subsonic Icing Wind Tunnel

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Abstract: Droplets generation in wind tunnels plays a crucial role in studying the factors contributing to ice formation on aircrafts. The liquid water content (LWC) and median volumetric diameter (MVD) are critical parameters influencing ice formation due to their impact on the rate of ice accumulation (frost, icing, or mixed), significantly affecting aircraft performance. Controlling these parameters is therefore essential when designing a test bed for characterizing systems sensitive to ice formation. In this paper, a nonlinear cascade fuzzy control structure is employed to control both the LWC and MVD obtained with a system injecting a mix of air and water in a refrigerated wind tunnel. This wind tunnel is purposed to accommodate the aforementioned systems to characterize. The desired values for MVD and LWC are used to determine setpoints for the water and air flows through the injection system. These setpoints serve as inputs for an internal control loop, where a PI controller is used to adjust the injector's valves' opening and control the flows. The efficiency of the proposed control is illustrated through simulation results.

Keywords: Fuzzy control, Subsonic icing wind tunnel, Liquid water content (LWC), Median volumetric diameter (MVD).

1. INTRODUCTION

Plants meant to operate in cold temperatures, such as aircrafts, can be subject to the formation of ice, modifying their performance. It follows that the plant's subsystems sensitive to ice formation have to be characterized. Thus, we need to test them in a controlled environment such as icing wind tunnels. In such facilities typically classified according to their Mach number [1], considerable work has been conducted to study the physics and nature of ice formation on structures or surfaces [2]. It has been concluded that it is necessary to inject, in the test section, water droplets of which liquid water content (LWC) and median volumetric diameter (MVD) are identified as crucial parameters closely associated with the process [3]. Therefore, controlling LWC and MVD in such a section is essential.

In the literature, various advanced control strategies have been explored for wind tunnels. In [1], feedforward control of stagnation pressure in a supersonic wind tunnel is discussed, while [4] introduces a nonlinear cascade control method for improving stagnation pressure control in a supersonic blowdown wind tunnel. In [5], a neural network-based model is presented within a model predictive control scheme and compared to proportional integral derivative control for Mach number in a closed wind tunnel. Additionally, a feedforward neural control is proposed in [6] to control test section temperature in a closed low-speed wind tunnel. In [7], the authors enhanced control performance with a neural network model predictive control optimising the operating parameters of the wind

tunnel. Fuzzy control methods are also investigated. In [8], a proportional derivative fuzzy logic control for plenum stagnation temperature is developed. In [9], fuzzy logic control is further enhanced by optimising the parameters of the membership function using neural networks.

To the best of our knowledge, there are no references where closed-loop control of LWC and MVD variables is proposed and implemented, despite the significant impact of these two parameters on structural icing. This motivates the current study. The contribution of this work is therefore the development of an uncoupled fuzzy control strategy to control the LWC and MVD, ensuring that these parameters remain within the range of values obtained in real experimental data [10]. This control strategy is then implemented and used in simulation to verify its efficiency.

The remainder of this paper is organized as follows. Section 2 is devoted to the description of the considered experimental plant and its mathematical model. The control algorithm is detailed in Section 3. Section 4 then presents some simulation results. Finally, concluding remarks and prospects are given in Section 5.

2. EXPERIMENTAL SETUP

In this section, we provide a brief introduction to the experimental plant under consideration. It consists in a subsonic icing wind tunnel and its constituent subsystems as shown in Figure 1.

This experimental plant consists in two main subsystems, namely the water and air injection system and the wind tunnel associated with a cooling chamber. More details about the system studied and the experimental facility can be found in [10].

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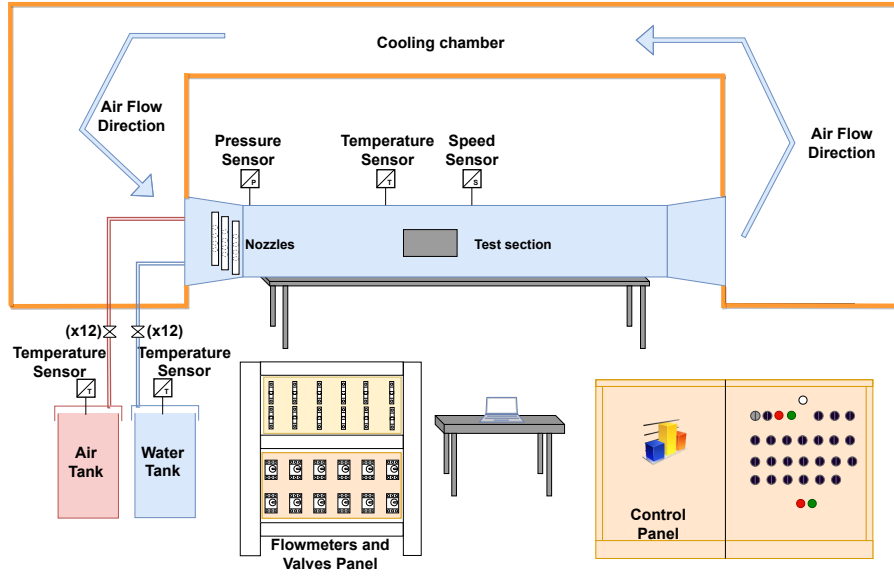


Fig. 1.: Testbed scheme.

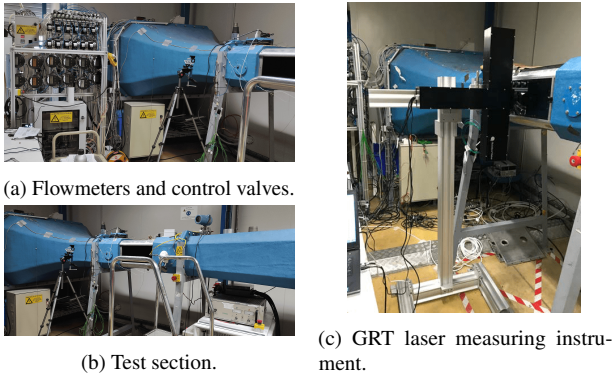


Fig. 2.: Wind tunnel facilities.

2.1 Plant description

System consists in a water and an air tank. Each tank is connected to 12 pipes, which in turn are connected to 12 identical control valves. Each valve is controlled using a proportional integral (PI) controller. A total of 24 control valves are used to control the air and water flows injected through the 12 nozzles, where water and air are mixed and injected into the test section. Flowmeters are used to measure water and air flows through the 24 pipes, as shown in Figure 2(a). Figure 2(b) displays the front part of test section where the velocity and temperature of the wind are controlled throughout the experiment by external control systems.

Various sensors are installed on the plant. First, temperature sensors provide the temperature in the test section T_{TS} , in the water tank T_w , in the air tank T_a , and in the nozzles T_n . All these temperatures are given in $^{\circ}\text{C}$. Second, the wind velocity v_{TS} in the test section is also measured and is given in $\text{m} \cdot \text{s}^{-1}$. Finally, the volumetric air flow per pipe Q_a , given in $\text{L} \cdot \text{min}^{-1}$, and the volumetric water flow per pipe Q_w , given in $\text{L} \cdot \text{h}^{-1}$, are also measured.

As there are usually no droplet LWC and MVD sensor

in the test section, a mathematical model providing the values of these parameters is required. This is the goal of the next subsection.

2.2 Mathematical modelling

For the purpose of modelling LWC and MVD, a special GRT laser measurement instrument, as shown in Figure 2(c), was temporarily installed inside the test section. However, as can be seen in Figure 2(c), the GRT instrument is placed into the test section at the location where the system we want to characterise has to be. It follows that it cannot be a permanent sensor providing LWC and MVD values in real time. With this instrument, thirty experiments were conducted in which LWC Λ , given in $\text{g} \cdot \text{m}^{-3}$, and MVD M , given in μm , are measured, while the quantities described in the previous section are also acquired.

In [10], equations that describe the behaviour of the water and air tanks, the flow control valves, the nozzles, and the test section and their interactions are developed, providing a mathematical link between LWC, MVD, and the operational parameters of these variables.

The LWC, which represents the mixing of the available mass of water m_{TS}^w within a defined air volume V_{TS}^a , is given by [11]:

$$\Lambda = \frac{m_{TS}^w}{V_{TS}^a}. \quad (1)$$

In (1), the volume is such that $V_{TS}^a = v_{TS} A_{TS}$, with A_{TS} the cross-sectional area of the test section, and the mass of water such that $m_{TS}^w = \rho_w Q_w$, with ρ_w the water density. Consequently, the LWC can be rewritten as

$$\Lambda = \frac{\rho_w Q_w}{v_{TS} A_{TS}}. \quad (2)$$

Estimating the MVD M is a more complex task. Various measurement devices [11] and machine learning techniques [12] have been used for this purpose. Consequently,

different machine learning-based models were proposed and compared in [10]. Ultimately, the polynomial model

$$\begin{aligned}
M = & 4.4380Q_a + 0.8825v_{TS} - 7.6323T_{TS} + 8.8270\Lambda \\
& - 0.0812Q_a v_{TS} + 0.8393Q_a T_{TS} + 0.1449v_{TS} T_{TS} \\
& - 0.9817Q_a \Lambda - 0.1066v_{TS} \Lambda + 0.4914T_{TS} \Lambda \\
& - 0.0141Q_a v_{TS} T_{TS} - 0.0037Q_a v_{TS} \Lambda - 0.1111Q_a T_{TS} \Lambda \\
& + 0.0189v_{TS} T_{TS} \Lambda - 0.0023Q_a v_{TS} T_{TS} \Lambda \quad (3)
\end{aligned}$$

was selected.

According to equations (2) and (3), the dynamics of LWC and MVD vary depending on the flow rates of water and air controlled by the valves. As shown in [10], Q_w is closely linked to the LWC variable, while Q_a is closely linked to the MVD variable.

3. CONTROL ALGORITHM

Controlling the LWC and MVD variables involves a highly nonlinear process. Moreover, these variables must be managed across diverse operating conditions. The control objectives aim to promptly achieve the desired values of LWC and MVD, while ensuring sufficient operational parameters within the study facility.

To maintain the desired LWC and MVD values in the test section, it is essential to control the flows around the desired values. This control is effectively achieved through an internal control loop based on a PI controller. As an external control loop, a cascade nonlinear control approach, based on the LWC and MVD dynamics, is proposed in this paper.

In fact, a direct uncoupled fuzzy control strategy is implemented, as described in [13]. This strategy allows for simple design and implementation and is designed to establish the desired setpoints of water and air flow for the internal controller, ensuring effective control of LWC and MVD in the test section.

For the uncoupled direct fuzzy control, two types of *Mamdani* fuzzy controller are implemented [14], one for each variable. These controllers operate independently, which means that there is no exchange of information between them. Each fuzzy controller is designed with two inputs and one output: the inputs are the error $e_\Lambda(t)$ or $e_M(t)$, with $e_\Lambda(t) = \Lambda_{des}(t) - \Lambda(t)$ and $e_M(t) = M_{des}(t) - M(t)$, and the derivative of the error $\dot{e}_\Lambda(t)$ or $\dot{e}_M(t)$, while the output is the control action that corresponds to $Q_w(t)$ or $Q_a(t)$, depending on the case. Figure 3 presents the control diagrams for both the LWC Λ and the MVD M .

For the LWC and MVD variables' error ($e_\Lambda(t)$, $e_M(t)$) and derivatives ($\dot{e}_\Lambda(t)$, $\dot{e}_M(t)$), three triangular membership functions are used. Each controller's output employs five triangular membership functions. The Center of Gravity (COG) method is employed for defuzzification.

Dealing with the fuzzy LWC controller, the domains of the error, the error derivative and the control action Q_w are $[-10, 10]$, $[-10, 10]$, and $[-6, 6]$, respectively. Similarly,

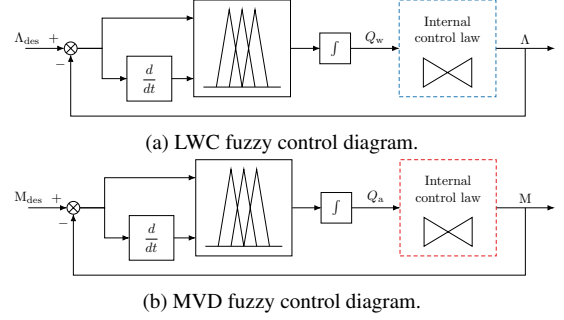


Fig. 3: LWC Λ and MVD M fuzzy control diagrams.

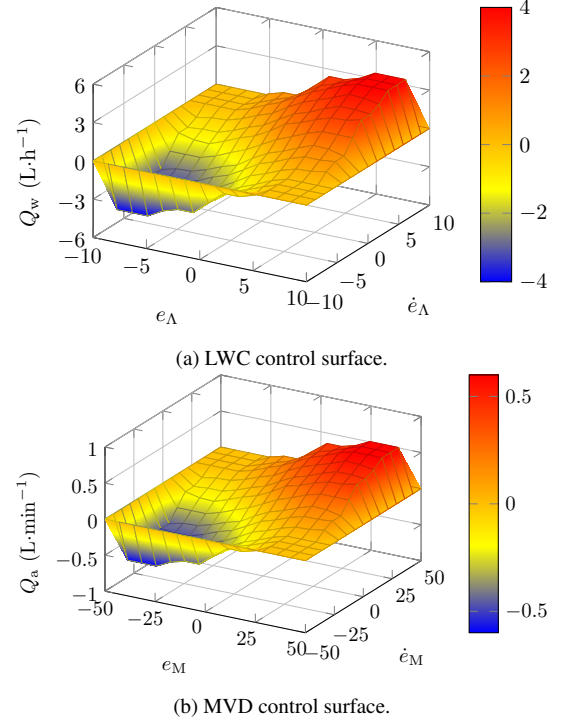


Fig. 4: LWC Λ and MVD M control surfaces.

Table 1: LWC Λ and MVD M fuzzy control rules.

	\dot{e}_Λ			\dot{e}_M		
	N	Z	P	N	Z	P
e	NB	NM	Z	PB	PM	Z
Z	NM	Z	PM	PM	Z	NM
P	Z	PM	PB	Z	NM	NB

in the MVD fuzzy controller, the domains for error, error derivative, and Q_a control action are $[-50, 50]$, $[-50, 50]$, and $[-0.9, 0.9]$, respectively. These ranges have been tuned through various simulations under different scenarios, depending on the number of valves used. Figure 4 depicts the fuzzy control surfaces for LWC and MVD.

Nine decision rules are defined for each controller, detailed in Table 1, where the terms *N*, *Z*, and *P* represent Negative, Zero, and Positive, respectively. Additionally, *NB*, *NM*, *PM*, and *PB* correspond to Negative Big, Negative Medium, Positive Medium, and Positive Big, respectively.

Although fuzzy controllers are defined in a very similar

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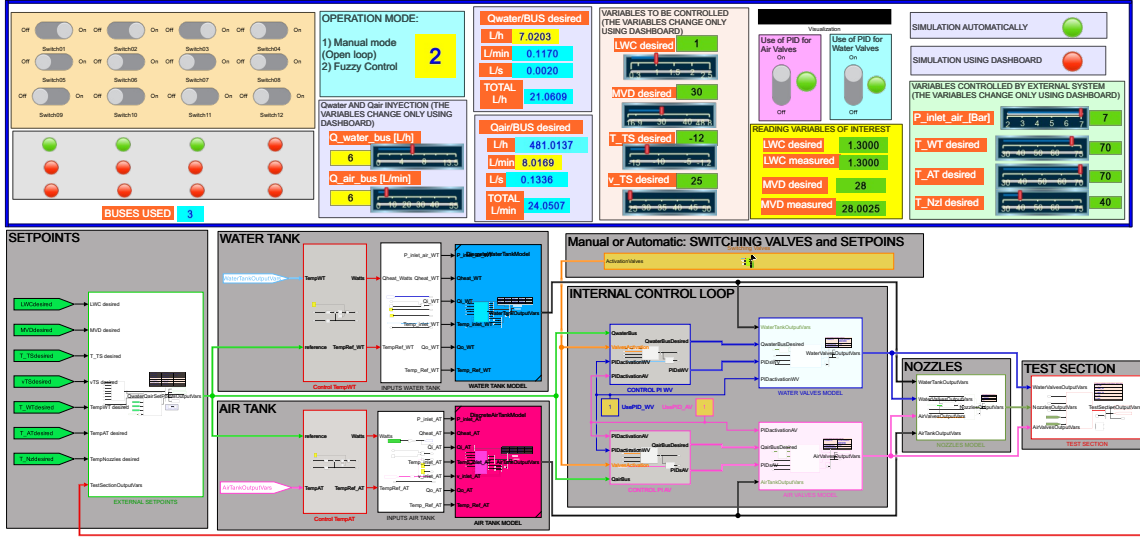


Fig. 5.: Control Simulink diagram.

manner, the inversion of rules in the MVD control compared to the LWC control is due to a higher Q_a results in a lower MVD and reciprocally, as shown in [10].

4. RESULTS

The cascade nonlinear control and the mathematical model are developed as interconnected modules in the Matlab/Simulink environment. A dashboard is designed to modify various scenarios of plant operation, as depicted in Figure 5. The dashboard includes several functionalities:

- The operating mode can be selected: manual mode (open loop) or fuzzy control mode.
- If a PI controller (either for water or air) malfunctions, a safety system is implemented to shut down all operations.

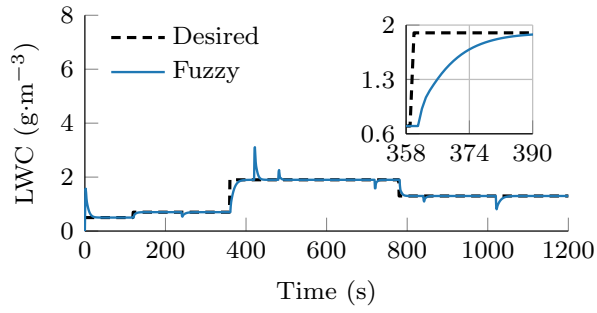
The uncoupled fuzzy control is applied in the external control loop of the studied plant. The results presented in this section are obtained considering the following information:

- It is assumed that the water and air temperatures are always controlled at a desired reference value of 70°C as mentioned in [10]. The useful temperature range for the experiment is between 60°C and 75°C .
- The PI controls (in the internal control loop) of the flow control valves act on area of the valves' opening.
- The temperature (T_{TS}) and the velocity (v_{TS}) in the test section are considered variables controlled by an external system.
- A simulation of an experiment lasting 20 minutes using a sample time of 1 s is performed. In this simulation, changes in the temperature of the test section as well as in the velocity of the test section, are considered. The simulation is carried out for different reference of both LWC and MVD. Additionally, different valves are activated and deactivated throughout the experiment.
- The following initial conditions are considered in the simulation run: $Q_w(0) = 5 \text{ L} \cdot \text{h}^{-1}$, $Q_a(0) = 5 \text{ L} \cdot \text{min}^{-1}$,

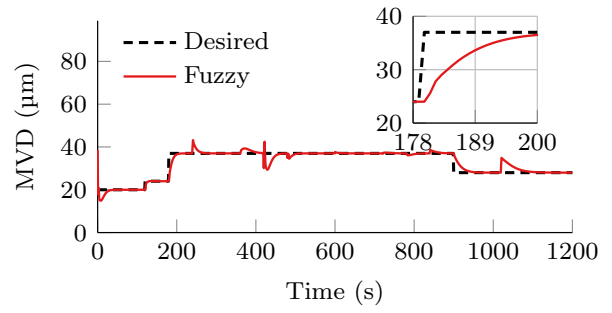
$v_{TS}(0) = 25 \text{ m} \cdot \text{s}^{-1}$, $T_{TS}(0) = -12^\circ\text{C}$, and four pipes operating.

The results of the proposed control are illustrated in Figure 6. In Figures 6(a) and 6(b), changes in the LWC and MVD references can be observed. On the one hand, at time 358 s, a considerable change of the LWC reference from 0.7 to $1.9 \text{ g} \cdot \text{m}^{-3}$ is applied and the fuzzy control manages to reach the reference in approximately 30 seconds. On the other hand, at 178 s, a significant change in the MVD reference is applied from 24 to $37 \mu\text{m}$, and the fuzzy control reaches the reference in about 20 seconds. Figures 6(c) and 6(d) shown the error for LWC and MVD when applying the fuzzy control. Furthermore, Figures 6(e) and 6(f) illustrate the control actions, specifically the total flow of water and air. Throughout the simulation, various changes can be seen in Figures 6(a) and 6(b), where the control works correctly and returns to the desired setpoint. For instance, the changes at 420 s and 1020 s are due to changes in the number of pipes used, changing from 3 to 5 and from 5 to 3, respectively, as seen in Figure 6(i). When there is a change in the number of pipes used, it causes a change in the total flow of both water and air. However, the LWC and MVD must remain controlled at the desired reference. Another change is observed in 720 s, due to a change in the velocity of the test section (see Figure 6(j)). Additionally, a change at 600 s affects only the MVD variable, caused by a change in the temperature of the test section (Figure 6(j)), which is a variable related only to MVD and not to LWC.

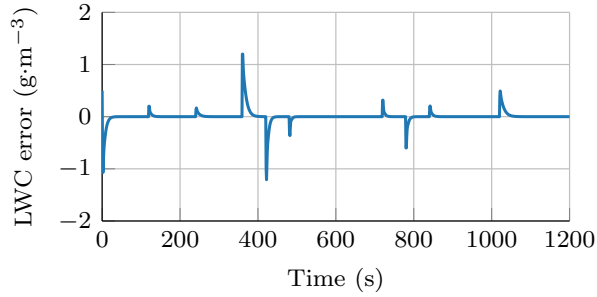
To observe the behaviour of the control valves in the internal control loop, they have been activated randomly during the simulation. During the simulation, only six valves have been activated. Figures 6(g) and 6(h) show the results of the water and air flows provided by the valves, controlled by the PI controller in the internal control loop. The valves (considered both the water and air valves) 1 are turned off and activated at 240 s and 480 s, respectively. Valves 2 and 3 are considered to be always in operation.



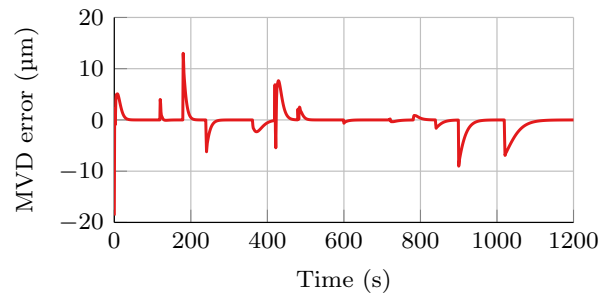
(a) LWC desired and control.



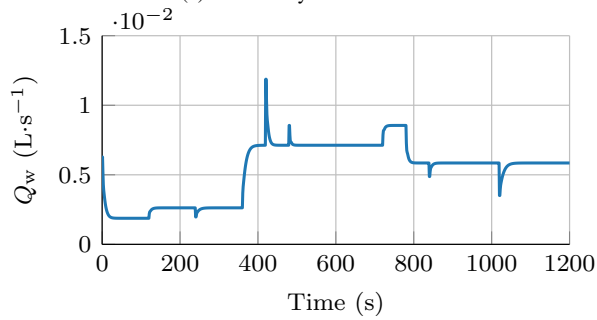
(b) MVD desired and control.



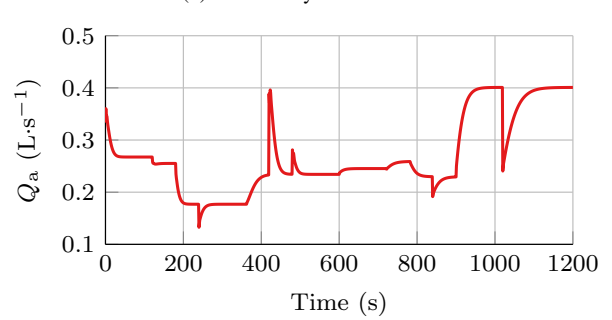
(c) LWC fuzzy control error.



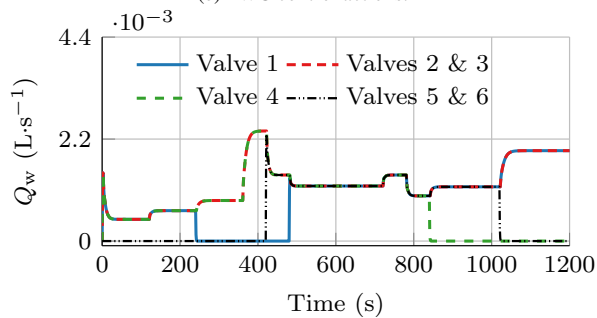
(d) MVD fuzzy control error.



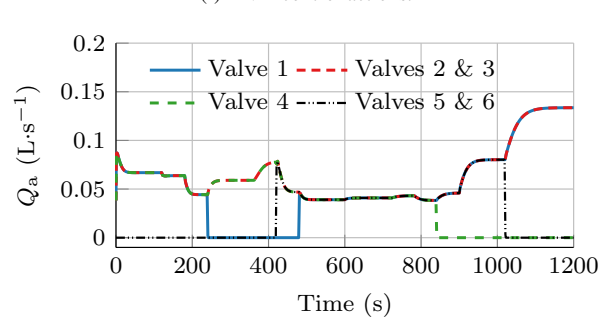
(e) LWC control actions.



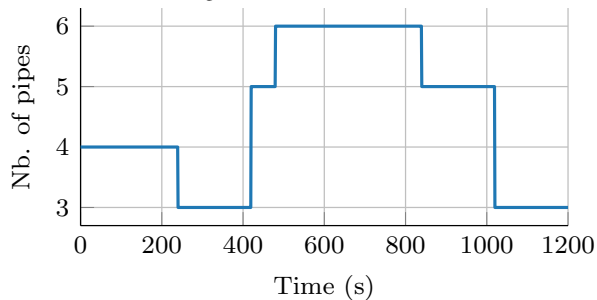
(f) MVD control actions.



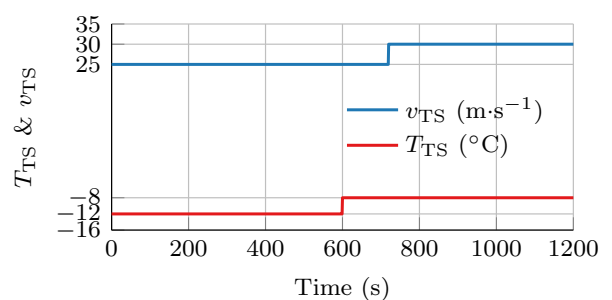
(g) Water valves actions.



(h) Air valves actions.



(i) Number of pipes used.



(j) Temperature and velocity in test section.

Fig. 6.: LWC and MVD desired trajectory, errors and control actions applying fuzzy control.

Valves 4 are considered to be switched on until 840 s, at this second it is switched off. Finally, valves 5 and 6 are initially considered to be switched off, then, at 419 s they are switched on, and, at 1020 s they are switched off. The flow provided by the internal water and air control valve varies depending on the setpoint given by the external control system.

The results indicate that the uncoupled fuzzy control approach exhibited satisfactory performance in managing LWC and MVD within the test section.

5. CONCLUSIONS AND FUTURE WORK

In this paper, a nonlinear cascade control structure was implemented to control the liquid water content and median volumetric diameter within the icing wind tunnel. In addition to this structure, parallel architecture PI anti-windup controllers have been used to track the air and water flow references necessary to maintain the desired LWC and MVD values in the test section. These setpoints have been enforced by an external fuzzy control system, which has shown effective control of both LWC and MVD in the test section, demonstrating its ability to handle system dynamics.

During experimentation, the fuzzy control parameters were heuristically tuned to achieve the desired system performance. In future work, the relationship between LWC and MVD will be considered, and therefore a coupled fuzzy control will be implemented. Furthermore, the parameters will be optimised using evolutionary optimisation and reinforcement learning techniques. The optimisation will be conducted within a multi-objective framework, taking into account both economic and technical aspects of the study plant. Additionally, model predictive control strategies will be developed and compared with fuzzy control implemented in this study.

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