Master and Auxiliary Compound Control for Multi-Channel Confluent Water Supply Switching Control Based on Variable Universe Fuzzy PID

Ge Zhao 1,*, Jian Wang 2, Wei Li 1, and Jinsong Zhu 1

1 School of Mechanical and Electrical Engineering, China University of Mining and Technology, Xuzhou 221116, China; zero166cmee@cumt.edu.cn (G.Z.); cmeezjs@cumt.edu.cn (J.Z.)
2 College Student Innovation Training Center, China University of Mining and Technology, Xuzhou 221116, China; Jian881028@cumt.edu.cn
* Correspondence: liweicmee@cumt.edu.cn

Received: 23 September 2020; Accepted: 9 November 2020; Published: 10 November 2020

Abstract: During the multi-channel confluent water supply process, the pressure control of the main pipe is often held back by such problems as non-linearity, hysteresis and parameter uncertainty, its own unique load dynamic changes, channel switching disturbance and other system characteristics caused by the actual working conditions. Moreover, pressure fluctuations in the main pipe will lead to a reduction in the service life of fire-fighting equipment, an increase in the failure rate, and even an interruption of the fire-fighting water supply. Therefore, a master and auxiliary control strategy is proposed to stabilize the pressure change in the process of multi-channel concentrated water supply switching, by using variable universe fuzzy proportional integral derivative (PID) control as the main controller on the main pipe and traditional PID control as the subsidiary controller on the channel. The control strategy is verified by the co-simulation platforms of LabVIEW and AMESim. Simulation results show that the variable universe fuzzy PID control and the master and auxiliary compound control based on the variable universe fuzzy PID control have advantages in step response, tracking response and anti-interference, respectively. The parameters obtained in the co-simulation are used in the experimental system. The experimental results show that the maximum deviation rate of main pipe pressure can be reduced by about 10% compared with other control methods under different loads. In conclusion, the proposed control strategy has strong anti-interference ability, fast dynamic response speed, high stability and good peak shaving effect.

Keywords: multi-channel confluent supply; variable universe fuzzy PID; pressure control; co-simulation platform; LabVIEW and AMESim; master and auxiliary control strategy

1. Introduction

Fire water supply is an important component in fire-fighting and rescue operations, and plays a key role in determining its success or failure. Fire water supply is developing in the direction of high efficiency and high stability with the increasing complexity of fire accidents and the increasing number of fire truck dispatches. As the pivotal aspect of the fire water supply, the multi-channel confluent water supply (MCCS) system is very important in ensuring the efficiency of water supply for fire-fighting and rescue work. In the event of large-scale fires, especially a fire located in a city with limited space, not only the is flow of fire-fighting water supply required, but there is also a higher demand for the stability of the water supply. The process of channel switching will inevitably occur in the multi-channel confluent water supply, which will lead to the pressure change of the water supply system. The common manifestation of pipeline pressure changes is water hammer, which can
cause major damage to the water supply system. For example, references [1–3] describe in detail the failure of water supply pipes due to the water hammer effect. Reference [4] analyzes the factors that affect pressure variation in the water supply system, such as power outages, pump shut-downs, valve operation, flushing, fire-fighting and main breaks. For a fire water supply system, changes in the pressure of the system will cause cavitation of the subsequent on-board pump, the fire extinguishing performance will be affected due to the large fluctuation of the terminal fire monitor, and the precision of the foam proportional mixing system is limited. Therefore, it is necessary to use appropriate switching methods and control strategies to minimize the pressure change caused by switching under the premise of ensuring the minimum energy loss, so as to ensure the continuity and stability of water supply.

The MCCS device consists primarily of a cluster structure, control system and additional equipment. In reference [5], the authors carried out a detailed analysis of the structure under the clustering conditions. The actuator of the control system is a pipeline valve. At present, proportional integral derivative (PID) controllers are mostly used to control pipeline valves in process control. This is because of their simple structure and low maintenance cost [6]. However, the traditional PID controller cannot achieve the ideal control effect due to the uncertainty of the object parameters and the nonlinearity and hysteresis of the MCCS system. In order to solve the deficiencies of the PID controller, various intelligent advanced control technologies have been developed in recent years. For example, Hamed et al. [7] use a sliding model controller to achieve the smoother and more rapid time responses of drum water level in a steam power plant, and the oscillation after control is smaller. Wu et al. [8] develop a stable model predictive tracking controller for coordinated control of a power plant, which realizes the off-set free tracking of the system under a wide range load variation. Liu et al. [9] propose an adaptive fuzzy PID controller with compensation correction, which successfully realizes the pressure control of the tractor, and has a better dynamic performance. Liang et al. [10] propose an improved genetic algorithm optimization for a fuzzy controller, which realizes the accurate closed loop of the wellhead back pressure system.

The control technology combined with these different advanced control methods has reached the control goals of most control systems in terms of control accuracy, response speed and robustness. Taking the combination of fuzzy control and traditional PID control as an example, domestic and foreign researchers have also conducted a lot of research in different application scenarios. Wang et al. [11] adopt fuzzy adaptive PID control to realize the stable control of grouting pressure with uncertain, time-varying and nonlinear characteristics, and its performance indicators are better than traditional control methods. In reference [12], a fuzzy PID controller is designed to control the steam temperature of the supercritical lignite boiler, and its excellent response speed and stability are verified through simulation. References [13,14] introduce the idea of a variable theory domain on the basis of a fuzzy PID control, which overcomes the shortcoming of the limited control rules of a fuzzy PID controller, further increases the controller’s adaptive ability, and improves the dynamic characteristics of the control system. In addition, references [15–17] use variable universe fuzzy PID control in different applications, and the control effect is significant.

In practical applications, the MCCS systems have common control system characteristics, such as non-linearity, hysteresis and parameter uncertainty, but also have their own unique load dynamic changes, channel switching disturbance and other system characteristics caused by the actual working conditions. Therefore, the multi-controller compound control is proposed by researchers, which is suitable for more complicated control systems or devices with higher control accuracy requirements. For example, reference [18] proposes a control method combining fuzzy PID and implicit generalized predictive control. Simulation experiments show that it can reduce the variation amplitude of the main steam pressure in the marine steam power system during the dynamic change process, and improve the response speed. Teresa et al. [19] propose a control strategy that is a combination of a fuzzy sliding film controller and a linear controller for the speed control of dual-mass drives, which has been verified by experiments and simulations. Song et al. [17] propose a new type of double closed-loop
control, chaos optimization and adaptive fuzzy PID compound control strategy for variable spray systems with large inertia, large hysteresis, nonlinearity, etc., and a satisfactory control effect is obtained through experimental verification. In reference [20], a compound controller based on fuzzy logic is proposed for the steam supply system of a nuclear power plant. Two local controllers are coordinated according to the working conditions based on the neural network PID controller and the fuzzy controller. The simulation results show that the control effect is a smoother and more stable operating performance.

In this paper, based on the change law of pressure in the process of MCCS switching, a master and auxiliary control strategy is proposed. On this basis, a co-simulation platform is built to verify the effectiveness of the proposed control strategy, and the effectiveness of the proposed control strategy is compared with that of the single fuzzy PID and the single variable theory domain fuzzy PID control. The advantages of the proposed composite control strategy are verified. The control strategy is tested and verified on the test bench, which further proves that the main and auxiliary compound control based on the variable universe fuzzy PID control can effectively optimize the pressure change of the main pipe. The paper is organized as follows. In Section 2, we build a research platform and co-simulation platform of the MCCS system. In Section 3, we design the master and auxiliary compound controllers. Then, in Section 4, we give simulation results and experimental results to demonstrate the superiority of the compound control strategy compared with single control. Finally, in Section 5, we summarize this paper.

2. System Modeling

2.1. MCCS Research Platform

The composition of the MCCS system of the research platform in this paper is shown in Figure 1. The system has four channels and one main pipeline. The medium water is pumped out of the water tank by the centrifugal pump through the filter. The pressure water of the four channels is collected into the main pipeline and led into the tank. The frequency converter in the control cabinet controls the speed and opening and closing of the centrifugal pump, and each channel has check valves, hand valves, pressure transducers, electric control valves and other components. A pressure transducer and a flow meter are installed on the main pipe to measure the pressure and flow of the main pipe. The main electric control valve is the executive structure of the controller, and the pipe load simulation ball valve is used to simulate pipeline resistance. The acquisition control system of the test platform consists of the chassis cDAQ-9185 of the American instrument NI, the acquisition card NI9203 and the output card NI9266. The main hardware parameters of the research platform are shown in Table 1.
Table 1. Research platform main hardware parameters.

| Device                        | Main Parameters                                      |
|-------------------------------|------------------------------------------------------|
| Centrifugal pump              | Model KSL32-160, flow rate 5 m$^3$/h, head 32 m, power 1.5 kW |
| Channel control valve         | Input signal 4–20 mA, PN1.0                          |
| Main control valve            | Input signal 4–20 mA, PN1.0                          |
| Main flowmeter                | Flow range 2–20 m$^3$/h, accuracy 0.5% FS, output signal 4–20 mA |
| Channel flowmeter             | Flow range 0.8–8 m$^3$/h, accuracy 0.5% FS, output signal 4–20 mA |
| Pressure transducer           | Range 0–0.6 MPa, accuracy 0.5% FS, output signal 4–20 mA |
| Acquisition control system    | Acquisition card NI9203 eight input channels, input signal 0–20 mA, sampling rate 200 kS/s |
|                              | Output card NI9266 eight output channels, output signal 0–20 mA, rate 24 kS/s/ch |
|                              | chChassis cDAQ9185 four slots, rate 1.6 MS/s        |

2.2. Mathematical Model

Multi-channel concentrated water supply means that multiple channels are connected in parallel in the same aggregate main pipe, and the switching process is its typical working condition. In fact, the switching process of the two channels is as follows: under the parallel operation of the water supply pump of each channel, the opening degree of the control valve in the operating branch gradually decreases from 100% to zero, while the control valve in the standby branch gradually increases from closed to 100%. If the action between the operating channel control valve and the standby channel control valve is not coordinated during the switching process, the pressure and flow rate in the collection main pipe will change, resulting in a big sudden change in the pressure in the main pipe. Due to the complex internal mechanism of the MCCS process, the mathematical model cannot be precisely established, and only an approximate model based on experience and test data for approximate processing can be established. The established model makes the following simplifications and assumptions: the system medium is water at room temperature and pressure; the fluid is in a single-phase flow state; the transient flow in the pipeline is one-dimensional and homogeneous. The numerical models of the key components of the whole system are established respectively.

The pressure and flow rate of the MCCS system will change during the switching process, which belongs to the transient flow state of the pipeline. The basic equation is composed of a mass conservation equation (continuity equation), a momentum conservation equation (motion equation) and an energy conservation equation (Bernoulli equation) in the transient process [21].

Continuity equation:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho v_x)}{\partial x} + \frac{\partial (\rho v_y)}{\partial y} + \frac{\partial (\rho v_z)}{\partial z} = 0
\] (1)

where $\rho$ is density, and $v_x, v_y$ and $v_z$ are the mean velocity in the $x, y$ and $z$ directions, respectively.

According to the model simplification, the pipeline flow is a one-dimensional single-phase incompressible transient flow, and the amount of flow in and out of a certain section of the control body along the pipeline is equal, namely:

\[
\frac{\partial v_x}{\partial x} + \frac{1}{\rho A} \frac{d(\rho A)}{dt} = 0
\] (2)

where $A$ is the cross-sectional area of a pipe.

Motion equation:

\[
\begin{align*}
  f_x - \frac{1}{\rho} \frac{\partial p}{\partial x} &= \frac{\partial v_x}{\partial t} + v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} + v_z \frac{\partial v_x}{\partial z} = \frac{dv_x}{dt} \\
  f_y - \frac{1}{\rho} \frac{\partial p}{\partial y} &= \frac{\partial v_y}{\partial t} + v_x \frac{\partial v_y}{\partial x} + v_y \frac{\partial v_y}{\partial y} + v_z \frac{\partial v_y}{\partial z} = \frac{dv_y}{dt} \\
  f_z - \frac{1}{\rho} \frac{\partial p}{\partial z} &= \frac{\partial v_z}{\partial t} + v_x \frac{\partial v_z}{\partial x} + v_y \frac{\partial v_z}{\partial y} + v_z \frac{\partial v_z}{\partial z} = \frac{dv_z}{dt}
\end{align*}
\] (3)
where \( p \) is pipe pressure, and \( f_x, f_y \) and \( f_z \) are the unit mass force in the \( x \), \( y \) and \( z \) directions, respectively. According to the model simplification, it can be obtained as follows:

\[
\rho A \frac{dv_x}{dt} + A \frac{\partial p}{\partial x} + \pi Dv = 0
\]

(4)

where \( D \) is pipe diameter.

Bernoulli equation:

\[
z + \frac{p}{\rho g} + \frac{v^2}{2g} = \text{const}
\]

(5)

According to the assumption, the model pipeline is a horizontal pipeline, and the equation is:

\[
\frac{p_A}{\rho g} + \frac{v^2_A}{2g} = \frac{p_B}{\rho g} + \frac{v^2_B}{2g} + \sum h_w
\]

(6)

where \( p_A \) and \( p_B \) are the pressure at point A and B of a certain pipe, respectively, \( v_A \) and \( v_B \) are the mean velocity at point A and B of a certain pipe, respectively, and \( h_w \) is the energy loss from pipe A to pipe B.

2.2.1. Component Models

For the pipeline structure of the MCCS shown in Figure 2, according to the conservation of mass, the flow rate through the concentrated water supply device at any instant meets the following conditions:

\[
Q_1 + Q_2 + Q_3 + Q_4 = Q_0
\]

(7)

\[
v_1A_1 + v_2A_2 + v_3A_3 + v_4A_4 = v_0A_0
\]

(8)

![Figure 2. Schematic diagram of MCCS pipe structure.](image)

According to the conservation of energy, the pipeline structure of the MCCS device meets the following requirements:

\[
\begin{align*}
\frac{p_1}{\rho g} + \frac{v^2_1}{2g} & = \frac{p_0}{\rho g} + \frac{v^2_0}{2g} + h_{w1-0} \\
\frac{p_2}{\rho g} + \frac{v^2_2}{2g} & = \frac{p_0}{\rho g} + \frac{v^2_0}{2g} + h_{w2-0} \\
\frac{p_3}{\rho g} + \frac{v^2_3}{2g} & = \frac{p_0}{\rho g} + \frac{v^2_0}{2g} + h_{w3-0} \\
\frac{p_4}{\rho g} + \frac{v^2_4}{2g} & = \frac{p_0}{\rho g} + \frac{v^2_0}{2g} + h_{w4-0}
\end{align*}
\]

(9)

where \( Q_1, Q_2, Q_3, Q_4 \) and \( Q_0 \) are the flow of section 1–1, section 2–2, section 3–3, section 4–4 and section 0–0 of the Figure 2, respectively, \( v_1, v_2, v_3, v_4 \) and \( v_0 \) are the mean velocity of section 1–1, section 2–2, section 3–3, section 4–4 and section 0–0 of the Figure 2, respectively, \( A_1, A_2, A_3, A_4 \) and \( A_0 \) are the cross-sectional area of section 1–1, section 2–2, section 3–3, section 4–4 and section 0–0 of the Figure 2, respectively, \( p_1, p_2, p_3, p_4 \) and \( p_0 \) are the pressure of section 1–1, section 2–2, section 3–3, section 4–4
and section 0–0 of the Figure 2, respectively, and $h_{wi-0}$ is the energy loss from section $i-i$ to section 0–0 of the Figure 2, $i = 1, 2, 3, 4$.

The classic method for analyzing the total flow and pressure of centrifugal pumps in parallel is the graphical method. This method is simple and convenient, but it does not reflect its internal mechanism, and the error is relatively large. At present, the characteristic curve of a single centrifugal pump and the characteristic curve of pipe resistance are mostly obtained by the quadratic polynomial fitting.

$$H_i = K_1 + K_2 Q_i + K_3 Q_i^2$$  \hspace{1cm} (10)

$$H_{res} = H_s + K_0 Q_i^2$$  \hspace{1cm} (11)

where $H_i$ is the centrifugal pump head, $H_{res}$ is the head of the pipeline/device, $H_s$ is the static head of the pipeline/device, $K_1$ is the constant, $K_2$ and $K_3$ are the characteristic curve fitting coefficients, $K_0$ is the coefficient of the pipe resistance characteristic curve, and $Q_i$ is the centrifugal pump flow.

The characteristic curve of the same type of centrifugal pumps in parallel is obtained according to the principle of the “addition of flow under the same head” of the characteristic curve of a single pump. Therefore, the characteristic curve of the parallel pump group can also be described by a quadratic polynomial [22].

$$H = K_1 + \frac{1}{N} K_2 Q + \frac{1}{N^2} K_3 Q^2$$  \hspace{1cm} (12)

where $N$ is the number of centrifugal pumps in parallel.

The flow through the valve in a transient state is $Q$, and the pressure loss caused by it is $\Delta p$. The relationship between the two is expressed as follows [23]:

$$Q = \frac{S}{\sqrt{\lambda_v}} \sqrt{\frac{2 \Delta p}{\rho}}$$  \hspace{1cm} (13)

where $\lambda_v$ is the resistance coefficient of the ball valve, and $S$ is the flow cross-section of ball valve.

The corresponding relation of the proportion of the cross-sectional area $S$ to the full-pass area (area opening), spool rotation angle and ball valve opening (by percentage) is shown in Figure 3 below:

Figure 3. Relationship between ball valve opening, area opening and spool angle.
The clustered structure in the MCCS device is composed of tees, elbows, etc., and the local resistance caused by them is ignored in the calculation model. Therefore, the local resistance model is required to compensate for the system in the calculation.

The total head loss of the pipe is the sum of the head loss along the way and the local resistance loss:

\[ h_w = \left( \lambda_j + \lambda \frac{l}{d} \right) \frac{v^2}{2g} \]  

(14)

where \( \lambda_j \) is the coefficient of local resistance, \( \lambda \) is the coefficient of resistance along the way, \( l \) is pipe length and \( d \) is pipe diameter.

For pipe flow, \( Q = vA \), which is then combined with the above formula:

\[ Q = \sqrt{\frac{2gdA^2h_w}{\lambda_j d + \lambda l}} \]  

(15)

We then define the equivalent resistance coefficient \( R \), so the above formula can be simplified to:

\[ Q = \sqrt{\frac{h_w}{R}} \]  

(16)

\[ R = \frac{\lambda_j d + \lambda l}{2gdA^2} \]  

(17)

2.2.2. Dynamic Mathematical Model

Figure 4 is a schematic diagram of the dynamic characteristics of the multi-channel concentrated water supply process. The straight lines and boxes in the figure represent the relevant objects of the concentrated water supply process, including water supply systems, agglomeration structures, valves and pipes. Combined with the mathematical model of each component of the system and the simplified assumptions of the whole system, a dynamic mathematical model of the MCCS process can be obtained.

Figure 4. Schematic diagram of the dynamic characteristics of the multi-channel clustering process.
According to the principle of conservation of mass, the dynamic mathematical model of each channel can be obtained as follows:

\[
\begin{align*}
    P_i &= K_1 + K_2 Q_i + K_3 Q_i^2 \\
    Q_i &= \frac{S_i}{\sqrt{\frac{2}{\lambda_j d_i + A_i}}} \sqrt{\frac{2(P_{0i} - P_{ii})}{\rho}} = \sqrt{\frac{P_i - P_{0i}}{R_i}} \\
    R_i &= \frac{\lambda_j d_i + A_i}{2g d_i A_i^2} \\
    i &= 1, 2, 3, 4
\end{align*}
\]  

(18)

where \( P_i \) is the pressure at the outlet of the centrifugal pump of channel \( i, i = 1, 2, 3, 4 \), \( R_i \) is the equivalent resistance coefficient of the corresponding pipe in the figure, \( i = 1, 2, 3, 4, 5, 6 \), \( P_{ii} \) is the pressure at the junction of channel \( i \) and the gathering structure pipe, \( i = 1, 2, 3, 4 \), and \( P_{0i} \) is the pressure in front of the control valve on channel \( i, i = 1, 2, 3, 4 \).

According to the principle of the conservation of mass and energy, the dynamic mathematical model of the clustered water supply structure can be obtained as follows:

\[
2 \sum_{i=1}^{4} P_{ii} - 8P_5 = 4\rho + 2A_0^2\rho g R_5 - \rho A_0^2 \sum_{i=1}^{4} Q_i^2
\]

(19)

where \( P_5 \) is the pressure at the connection between the main pipe and the gathering structure pipe.

The dynamic mathematical model of the main pipe can be obtained as shown in the following formula based on the principle of conservation of mass. The control valve on the main pipe is the main regulating valve, and the valve resistance is much greater than the pipeline resistance, so the pipeline resistance is ignored.

\[
\rho \lambda_0 Q_0^2 - 2S^2 (P_5 - P_0) = 0
\]

(20)

The water-consuming system can be equivalent to a resistance element, which is replaced by a pipe load simulation valve. The pressure at the outlet of the water-consuming system is atmospheric, and its dynamic mathematical model is as follows:

\[
P_0 = R_7 Q_0^2
\]

(21)

where \( P_0 \) is the pressure before the load simulation valve, \( Q_0 \) is the flow before the load simulation valve, and \( R_7 \) is the equivalent resistance coefficient of the load simulation valve and its front and rear accessories.

Equations (18)–(21) represent the dynamic mathematical model of the MCCS process. Through this dynamic mathematical model, it can be seen that the main factors affecting the pressure of the main pipe are the pre-aggregate flow rate, the main pipe control valve and the equivalent resistance of the pipe load simulation valve.

2.3. Co-Simulation Platform Based on LabVIEW and AMESim

The co-simulation technology can reduce the dependence on the physical prototype, reduce the number of tests under the premise of obtaining reliable experimental data, and verify the feasibility of the control scheme in advance to avoid unnecessary losses. The joint simulation platform based on LabVIEW and AMESim is a dynamic link library (.dll file) generated by LabVIEW, called the AMESIM simulation model. Three subVIs are used to realize the data interaction between the LabVIEW and AMESim models, and realize the process operation and control of co-simulation.

2.3.1. Simulation Model Based on AMESim

The AMESim model in the co-simulation platform consists of two parts, as shown in Figure 5. The first part is the AMESim simulation model of MCCS, which can simulate different working conditions of multi-channel concentrated water supply. The second part is the interface module,
LabVIEWCosim, of the co-simulation, which provides AMEDoAstep2.VI, AMEEInitModel.VI and AMETerminate.VI, and realizes the LabVIEW and AEMSim signal transmission. In the simulation model, the pressure signal of the channel and the pressure signal of the main pipe are selected as the output of the simulation system and fed back to the controller. At the same time, the algorithm in the controller calculates the control value of the regulating ball valve and acts on the simulation system through the simulation interface.

**Figure 5.** Sketch of the AMESim simulation model: Part A is the AMESim simulation model of MCCS; Part B is interface module of the co-simulation platform.

A sketch of the MCCS simulation model is shown in Part A of Figure 5. It includes the MCCS structure, pump, valve, sensors, etc., and is slightly simplified compared to the real one. The Hydraulic and Hydraulic Resistance libraries are used to model the MCCS system. Taking into account the flow characteristic curve of the ball valve, the SIGUDA01 of the signal library is used to realize the relationship between the valve opening and the flow in modeling. Besides this, the parameters of the main components have been obtained from the experimental results and technical data sheets of the manufacturer. When building the model, it is necessary to ensure the mathematical transfer relationship between the component sub-models, and realize the output and input relationship of the front and back sub-models on the same pipeline [24]. The sub-models and parameters of the main components of the MCCS are shown in Table 2.

**Table 2.** Sub-models and parameters of main components.

| Component       | Parameter          | Value       | Component       | Parameter          | Value       |
|-----------------|--------------------|-------------|-----------------|--------------------|-------------|
| Centrifugal pump| Pump diameter      | 160 mm      | Tee friction coefficient | Trunk       | 0.4 |
|                 | Reference speed    | 2840 r/min  | (diversion)     | Trunk-channel      | 1.44        |
|                 | Efficiency         | 0.95        | Tee friction coefficient | Trunk       | 0.4 |
|                 | Flow rate pressure | 500 L/min/bar | (confluence)   | Trunk-channel      | 1.21        |
| Check valve     | Gradient           | 500 L/min/bar |                 |                   |             |
The verification of the MCCS simulation model includes two aspects: constant flow performance verification and unsteady flow performance verification. Constant flow performance refers to the pressure and flow of the main pipe when the system is stable. That is, the pressure and flow of the main pipe are recorded by turning on different numbers of centrifugal pumps and using different main pipe loads (the opening of the valve at the end of the main pipe simulates the pipe load). Unsteady flow performance verification refers to the characteristics of the main pipe pressure changing with time when the system status changes. For example, in the parallel operation of three channels and the standby of one channel, different switching signals are given to the channel control valve so that the standby channel can be switched with one of the parallel channels to obtain the time-varying characteristics of the pressure of the main pipe during the switching process, including synchronous switching, delayed switching and advanced switching. In the parallel operation of three channels, a control signal of 0–100% opening is given to the main regulating ball valve to obtain the time-varying characteristics of the pressure in the main pipe. The simulation model is set with the same parameters, and the results obtained are compared with the experimental results. The performance verification of constant flow and unsteady flow is shown in Figures 6 and 7, respectively.

It can be seen from Figure 6a that when different numbers of branches are connected in parallel, the pressure of the main pipe is inversely proportional to the opening of the pipe load simulation valve, and it conforms to the regulation law of the ball valve. That is, when the opening of the ball valve is between 80% and 100%, the pressure change is relatively gentle. There is little difference between the main pipe pressure value in the simulation model and the experiment, and the simulation and experiment have good consistency. Figure 6b shows that the flow of the main pipe is proportional to the opening of the pipe load valve, which also conforms to the regulation law of the regulating ball valve. Moreover, the increment of the main flow from three channels to four channels in parallel shows an increasing trend with the increase of the opening of the pipe load valve. It should be noted that when the pipe load valve opening is greater than 60%, the flow of the four-channel main pipe in parallel is greater than the range of the flowmeter (20 m$^3$/h), and there is no test value temporarily. However, from the comparison between the simulation value and the experimental value of the main flow of the three-channel pipe in parallel, it can be seen that the simulation model is also consistent with the test bench data sample. Therefore, it can be considered that the simulation model based on AMESim can replace the testbed for subsequent research when the multi-channel confluent water supply is constant.

Figure 6. Constant flow performance verification: (a) Main pipe pressure under different pipe loads; (b) Main pipe flow under different pipe loads.
Figure 7. Unsteady flow performance verification: (a) Main pipe pressure when switching between two channels; (b) Main pipe pressure of the main valve opening from 0 to 100%.

The control process of the multi-channel concentrated water supply system is an unsteady flow state for the main pipe pressure, that is, when the main control valve on the main pipe changes or the control ball valve on the channel changes, the flow state in the main pipe is not stable, and the main pipe pressure changes with time. The model based on AMESim not only needs to have a high degree of consistency with the research platform in the steady state of the system, but more importantly, the simulation model also needs to have a good dynamic consistency with the research platform when the system state changes. From Figure 7a, it is evident that when the switching time and switching sequence of the two channels are different, the fluctuation of the main pipe pressure will also change. Compared with the simulation model, the main pipe pressure before and after the switching is different. This is because the switching of two centrifugal pumps and channels cannot be exactly the same, resulting in different pressure values of the main pipe before and after the switch. From Figure 7b, we see that when the three channels are connected in parallel, the opening time of the main control valve is 5 s, and the pressure on the main control valve increases gradually with the opening of the main control valve. There is a difference between the simulated value and the test value when it is turned on. This is because there is a certain initial pressure at the beginning of the research platform, but the overall trend is the same, and the experimental value and the simulated value have a high degree of consistency after the turn-on. In a word, although the results of the experiment and the simulation model under constant flow and unsteady flow have certain errors, the overall trend is the same. It can be considered that the simulation model is a reproduction of the research platform, and the simulation model can be used for system control research.

2.3.2. Controller Model Based on LabVIEW

The model established in LabVIEW is a co-simulation master and auxiliary compound control system, which is divided into two parts: the front panel and the block diagram. The front panel is used for the operation interface of co-simulation, in which the control system parameters can be set, including the determination of PID control parameters, set value pressure, etc. The corresponding pressure curve can also be read in real-time. The model in LabVIEW completes the interactive function of the two-model data by recalling the '.dll' file generated in AMESim (see Figure 8). There are three input parameters and three output parameters in the simulation interface of AMESim for data interaction with LabVIEW.
After the MCCS co-simulation, in addition to observing the main pipe pressure change curve on the co-simulation operation control interface, more comprehensive and rich data can also be extracted from the AMESim software. For the same simulation process, the running results obtained from the operation control section are consistent with the simulation data directly extracted from AMESim, which proves that the co-simulation of LabVIEW and AMESim is correct.

3. Design of the Master and Auxiliary Compound Control

The function of the MCCS system is to meet the requirement of multiple water sources in supplying a piece of water-requiring equipment stably and continuously. According to the requirements of the MCCS system, the pressure of the MCCS device should not undergo a big sudden change on the premise that the flow rate after gathering meets the requirements, so as to avoid the adverse impact on the subsequent equipment. Especially when a channel must be switched due to the exhaustion of the water source, the pressure of the main pipe will inevitably fluctuate, causing instability in the entire water supply system and causing trouble in the use of terminal equipment. For example, pressure changes can cause cavitation in the centrifugal pump, and deviations in the drop points of water jets from fire monitors. Based on this, the control objective is obtained as follows: under the premise of meeting the water supply requirements, the terminal equipment can obtain continuous medium water and stable pipeline pressure. For switching conditions, the main pipe pressure can remain stable at the maximum value, reducing the pressure loss of the multi-channel concentrated water supply system and improving its efficiency.

The pressure adjustment of the MCCS system seems simple, but it is difficult to achieve better results with conventional industrial technology. The reason is that this system has unfavorable factors such as nonlinearity, large lag, and large interference. Therefore, this article provides a compound pressure control strategy, including two parts: the main controller and the sub-controller. The main controller controls the main control valve and quickly adjusts the pressure on the main pipe to near the set value. The sub-controller is selectively opened for non-switched channels to control the pressure fluctuations caused by changes in the resistance of the switched channels and interference of the front water supply system, playing an auxiliary role in the pressure stability of the main pipe. The sub-controller adopts incremental PID control, because the incremental PID itself will not cause valve jitter and is more suitable for the small-range adjustment of branch circuits. The main controller adopts variable universe fuzzy PID control. This is due to the uncertainty of the equipment connected...
to the MCCS system. The conventional fixed fuzzy PID control cannot effectively adapt to the changes in system characteristics, and it is difficult to achieve the requirement of the main pipe pressure control under variable working conditions. The variable universe fuzzy PID controller can adjust the fuzzy universe via the expansion factor according to the difference in main pipe pressure, and overcome the limitation of the conventional fuzzy PID controller's limited adaptive ability. In summary, the MCCS compound control structure is shown in Figure 9.

3.1. Variable Universe Fuzzy PID Controller

Variable universe fuzzy PID control introduces the idea of a variable universe on the basis of a adaptive fuzzy PID control, improves the robustness of the control system, expands its adaptive ability, and further improves the steady-state accuracy and dynamic response of the control system. The variable universe fuzzy PID controller is mainly composed of an adaptive fuzzy PID control module and the contraction–expansion factor adjustment module. In the operation of the system, the expansion factor adjustment module continuously adjusts the expansion factor of the output and input universe according to the main pipe pressure deviation and the deviation rate, and then changes the fuzzy universe in the adaptive fuzzy PID control module, so that the actual control rules always remain high, realizing the stability, anti-interference and adaptability of the controller. The structure principle of the variable universe fuzzy PID controller is shown in Figure 10.
3.1.1. Adaptive Fuzzy PID Control Module

Adaptive fuzzy PID control is a combination of fuzzy control and PID control. The main idea is to first establish the fuzzy relationship between the three parameters of PID and the deviation $e$ and deviation change rate $ec$, and then the real-time monitoring of $e$ and $ec$ and, according to the fuzzy logic PID controller of proportion, the integral and differential online adjustments.

The design of a fuzzy PID controller mainly consists of four parts: fuzzification, determination of membership function, the establishment of fuzzy control rules and defuzzification.

(1) Fuzzification of input and output

The structure of the fuzzy controller is a two-dimensional structure with two inputs and three outputs. The difference between the measured main pipe pressure and the coordinated set value is $e$. The deviation $e$ and the deviation change rate $ec$ are inputs, and the PID parameter adjustment values $\Delta K_p$, $\Delta K_i$ and $\Delta K_d$ are output. First, the deviation, deviation change rate, proportional coefficient increment, integral coefficient increment and differential coefficient increment are fuzzy processed, the quantization domains corresponding to them are determined, and the fuzzy language is used to express them. Through the experiment, the deviation range of the main pipe pressure under different working conditions is $[-0.06, 0.06]$, and the deviation change rate range is $[-0.9, 0.9]$. In the test process, the PID parameters are roughly tested according to the trial and error method, and the basic domain of the proportional adjustment can be obtained $([-3, 3])$. The basic domains of the integral coefficient and the differential coefficient adjustment are $[-3, 3]$ and $[-10, 10]$, respectively. The quantization domains corresponding to the input and output are both $[-6, 6]$. The fuzzy language variables are divided into seven levels, which are negative big (NB), negative medium (NM), negative small (NS), zero (ZO), positive small (PS), positive medium (PM), positive big (PB).

The input and output variables are summarized in Table 3.

| Variable | Basic Domain | Quantization Domain | Fuzzy Language |
|----------|--------------|---------------------|----------------|
| Input $e$ | $[-0.06, 0.06]$ | $[-6, 6]$ | [NB, NM, NS, ZO, PS, PM, PB] |
| Input $ec$ | $[-0.9, 0.9]$ | $[-6, 6]$ | [NB, NM, NS, ZO, PS, PM, PB] |
| Output $\Delta K_p$ | $[-3, 3]$ | $[-6, 6]$ | [NB, NM, NS, ZO, PS, PM, PB] |
| Output $\Delta K_i$ | $[-3, 3]$ | $[-6, 6]$ | [NB, NM, NS, ZO, PS, PM, PB] |
| Output $\Delta K_d$ | $[-10, 10]$ | $[-6, 6]$ | [NB, NM, NS, ZO, PS, PM, PB] |

(2) Determination of membership function

To obtain the analysis results quickly, reduce the complexity of the control system and improve the operation efficiency, the membership function adopts the triangular membership function. Given the characteristics of different working conditions of MCCS, the membership function is set to be sparse at both ends of the input universe and dense in the middle to meet the requirements of the rapid response of large deviations and the accurate regulation of small deviations. The membership functions of the input domain and the output domain are shown in Figure 11.
(3) Establishment of fuzzy control rules

According to the influence of the parameters \( K_p, K_i \) and \( K_d \) on the PID control output characteristics of the multi-channel concentrated liquid supply system, combined with the existing reference literature and the operating experience of the research platform, the PID parameter adjustment principle is designed, as follows.

General principle: When the deviation \( e \) is large, the deviation should be eliminated as soon as possible under the premise of ensuring the stability of the system; when the deviation \( e \) is small, the stability of the system is the main thing.

The fuzzy rules are shown in Table 4.

| \( e \)   | NB   | NM   | NS   | ZO   | PS   | PM   | PB   |
|--------|------|------|------|------|------|------|------|
| \( ec \) |      |      |      |      |      |      |      |
| NB     | PB/NB/PS | PB/NB/NS | PM/NM/NB | PM/NM/NB | PS/NS/NB | ZO/ZO/NS | ZO/ZO/PS |
| NM     | PB/NB/PS | PB/NB/NS | PM/NM/NB | PS/NS/NM | ZO/ZO/NS | NS/PS/NS | NS/PS/ZO |
| NS     | PM/NB/ZO | PM/NM/NS | PS/NS/NS | ZO/ZO/NS | NS/PS/NS | NM/PM/NS | NM/PM/ZO |
| ZO     | PM/NM/ZO | PM/NM/NS | PS/NS/NS | ZO/ZO/NS | NS/PS/NS | NM/PM/NS | NM/PM/ZO |
| PS     | PS/NM/ZO | PS/NS/ZO | ZO/PS/NS | ZO/ZO/NM | ZO/ZO/NS | ZO/ZO/PS | ZO/ZO/PM |
| PM     | PS/ZO/PB | ZO/ZO/NS | NM/PS/PS | NM/PM/PS | NM/PM/PS | NM/PM/PS | NB/PB/PB |
| PB     | ZO/ZO/PB | ZO/ZO/PM | NM/PM/PM | NM/PM/PM | NM/PM/PM | NM/PM/PM | NB/PB/PB |

Negative big (NB); negative medium (NM); negative small (NS); zero (ZO); positive small (PS); positive medium (PM); positive big (PB).

(4) Defuzzification

The centroid method is used to solve the fuzziness, and the precise adjustment value of the PID parameters is obtained. Then, the PID control parameters \( K_p, K_i \) and \( K_d \) are obtained by adding the initial values of the PID control parameters. The calculation formula is shown below.

\[
\begin{align*}
K_p &= K_{p0} + \Delta K_p \\
K_i &= K_{i0} + \Delta K_i \\
K_d &= K_{d0} + \Delta K_d
\end{align*}
\]  

(22)

where \( K_p \) is the scale factor, \( K_i \) is the integral coefficient, and \( K_d \) is the differential coefficient. \( \Delta K_p \) is the increment of the proportional coefficient, \( \Delta K_i \) is the increment of the differential coefficient, \( \Delta K_d \) is the increment of the integral coefficient, and \( K_{p0}, K_{i0} \) and \( K_{d0} \) are the initial proportional coefficient, initial differential coefficient and initial integral coefficient, respectively.
3.1.2. Contraction–Expansion Factor Adjustment Module

The idea of a variable domain can be understood as the domain of adjusted input and output variables according to certain control rules according to actual requirements. Let us set \([-E, E]\) and \([-EC, EC]\) as the initial universe of input variables \(e\) and \(ec\), respectively. The initial output domains of the proportional coefficient increment, \(\Delta K_p\), the integral coefficient increment \(\Delta K_i\) and the differential coefficient increment \(\Delta K_d\) are \([-Up, Up]\), \([-Ui, Ui]\) and \([-Ud, Ud]\), respectively. The initial domains are transformed into \([-a(e)E, a(e)E]\), \([-a(ec)EC, a(ec)EC]\), \([-\beta(kp)Up, \beta(kp)Up]\), \([-\beta(ki)Ui, \beta(ki)Ui]\) and \([-\beta(kd)Ud, \beta(kd)Ud]\) through the contraction–expansion factor, that is, the domain of work changes with the change in the contraction–expansion factor, ensuring the number of actual work fuzzy values is always in the highest position, and a relatively satisfactory control effect is obtained. The factors \(a(x)\) and \(\beta(x)\) are the contraction–expansion factors of the input and output domains, respectively. There are currently three design methods: the functional contraction–expansion factor, the fuzzy reasoning contraction–expansion factor, and the error classification contraction–expansion factor. This paper chooses the calculation method based on the fuzzy inference type contraction–expansion factor, because the contraction–expansion factor calculation model based on fuzzy rules satisfies the monotonicity, duality, coordination, normality and zero avoidance of the contraction–expansion factor, and avoids the functional contraction–expansion factor’s calculation model parameter selection [15,25]. At the same time, fuzzy rules are used to express the change law of the contraction–expansion factor to realize the online automatic adjustment of the contraction–expansion factor.

The contraction–expansion factor model based on fuzzy rules is based on the actual control deviation and deviation change rate, and uses easy-to-understand language to describe the change law of the universe. That is, the universe shrinks when the deviation becomes smaller, and the universe expands when the deviation becomes larger. The size of the quantization factor and the scale factor actually reflects the expansion change of the corresponding domain. The fuzzy reasoning expansion factor is used to establish another fuzzy controller on the basis of the basic fuzzy PID controller, in order to modify the parameters of the quantization factor and the scale factor.

(1) Input universe contraction–expansion factor fuzzy control

The contraction–expansion factors \(a(e)\) and \(a(ec)\) of the input universe are divided into five fuzzy language variables, which are extra-small (VS), small (S), medium (M), large (B), extra-large (VB). The uniform triangular membership distribution function is used, as shown in Figure 12a.

![Figure 12a](image12a.png)

**Figure 12.** The contraction–expansion factors’ membership functions: (a) Input variables \(a(e)\) and \(a(ec)\); (b) Output variables \(\beta(kp)\), \(\beta(ki)\) and \(\beta(kd)\).

The adjustment rules are as follows: when \(e\) and \(ec\) are large, the input domain should remain large; when \(e\) and \(ec\) are small, reduce the input domain to improve the pressure control accuracy, as shown in Table 5.
Table 5. Contraction–expansion factors a(e) and a(ec) fuzzy control rules.

| e  | NB | NM | NS | ZO | PS | PM | PB |
|----|----|----|----|----|----|----|----|
| NB | VB | VB | B  | M  | B  | VB | VB |
| NM | VB | B  | M  | S  | M  | B  | VB |
| NS | B  | M  | S  | VS | S  | M  | B  |
| ZO | M  | S  | VS | VS | S  | M  | M  |
| PS | B  | M  | S  | VS | S  | M  | B  |
| PM | VB | B  | M  | S  | M  | B  | VB |
| PB | VB | VB | B  | M  | B  | VB | VB |

Negative big (NB); negative medium (NM); negative small (NS); zero (ZO); positive small (PS); positive medium (PM); positive big (PB); extra-small (VS); small (S); medium (M); large (B); extra-large (VB).

(2) Output universe contraction–expansion factor fuzzy control

The contraction–expansion factors β(kp), β(ki) and β(kd) of the output universe are divided into seven fuzzy language variables, which are extremely-small (Z), very small (VS), pretty small (S), small (SB), medium (M), large (B), and extra-large (VB). A triangular membership function is used, as shown in Figure 12b.

The adjustment rule of the output universe contraction–expansion factor: when e and ec are large, and the signs of the two are the same, this indicates that the target value and the process variable are very different. At this time, there should be a large output control amount, which will make the process variable quickly track the target value. The contraction–expansion factor is larger in order to increase the output control amount. When e and ec are large and their signs are opposite, this indicates that there is a big difference between the target value and the process variable, but the difference is decreasing. In this case, the system should have a small output control quantity, which will ensure that the process variable can track the target value quickly without causing a big shock. In other words, a small value of the contraction–expansion factor is taken. When e is close to zero and ec is very large, this indicates that the difference between the process variable and the target value is very small, but the process variable is deviating from the target value at a very fast speed. At this time, the system should have a large output control amount to restrain the actual value from deviating from the target. The contraction–expansion factors β(kp), β(ki) and β(kd) and their fuzzy control rules are shown in Table 6.

Table 6. Contraction–expansion factors β(kp), β(ki) and β(kd) and their fuzzy control rules.

| e  | NB | NM | NS | ZO | PS | PM | PB |
|----|----|----|----|----|----|----|----|
| NB | VB/Z/M | VB/Z/S | B/VS/Z | B/VS/Z | B/VS/Z | M/S/Z | SB/SB/VS | SB/SB/M |
| NM | VB/Z/SB | VB/Z/S | B/VS/Z | M/S/VS | M/S/VS | M/S/VS | SB/SB/S | SB/SB/S |
| NS | B/VS/SB | B/VS/S | B/VS/S | M/S/VS | SB/SB/S | S/M/S | S/M/S | S/M/S |
| ZO | B/VS/SB | M/S/S | M/S/S | SB/SB/S | S/M/S | VS/B/S | VS/B/S | VS/B/S |
| PS | M/S/SB | M/S/SB | SB/SB/S | S/M/SB | S/M/SB | VS/B/S | VS/B/S | VS/B/S |
| PM | SB/SB/VB | SB/SB/M | S/M/M | VS/M/M | VS/B/M | VS/B/M | Z/VS/V | Z/VS/V |
| PB | SB/SB/VB | S/SB/B | S/M/B | VS/B/B | VS/B/B | VS/B/B | Z/VS/V | Z/VS/V |

Negative big (NB); negative medium (NM); negative small (NS); zero (ZO); positive small (PS); positive medium (PM); positive big (PB); extra-small (VS); small (S); medium (M); large (B); extra-large (VB).

3.2. Valve Controller

In the process of the MCCS, each channel and the main pipeline has a regulating ball valve. Due to the uncertain influence caused by the flow characteristics of the ball valve, the accuracy of the control volume is greatly affected. In addition, combined with the use of the multi-channel concentrated water supply system, that is, in order to obtain a large flow under the premise of pressure stability,
which requires the adjustment of the ball valve; the opening cannot be too small. Therefore, it is of great significance to increase the control module of the adjusting ball valve to control the multi-channel concentrated water supply system.

According to the flow characteristic curve of the ball valve, the local resistance coefficient is very small when the opening degree of the ball valve is 80–100%, and there is almost no change and no adjustment effect; when the opening degree of the ball valve is 0–50%, the local resistance coefficient increases sharply. Although the adjustment ability is strong, the flow rate is reduced greatly, which is contrary to the control objective of the multi-channel concentrated water supply system. When the opening degree of the ball valve is 50–80%, the local resistance coefficient gradually increases, which has a regulating effect, and the flow rate change amplitude is small. Therefore, combining the flow characteristic curve of the regulating ball valve and the actual operating conditions, the ball valve expert controller is designed.

When the opening of the ball valve is 0–50%, and the increment of the ball valve is $\Delta u$, then $u = 50\% + \Delta u$.

When the opening of the ball valve is 50–80%, and the increment of the ball valve is $\Delta u$, then $u = u + \Delta u$.

When the opening of the ball valve is 80–100%, and the increment of the ball valve is $\Delta u > 0$, then $u = 100\%$.

3.3. Pressure Set Point Coordinated Controller

In the process of MCCS, if the main pipe’s pressure value is set too low, most of the energy of the parallel channels will be lost, reducing the efficiency of the multi-channel concentrating water supply. The set value of the main pipe’s pressure is too high, and the regulating effect of the main pipe’s pressure is not obvious. Therefore, an important link to ensure the pressure stabilization effect and the water supply efficiency of the multi-channel concentrated water supply control is to coordinate and optimize the pressure-setting value.

There is an adjusting ball valve on each of the four channels, and the pressure fluctuation caused by switching can be adjusted by controlling the ball valve on the non-switching channels to play an auxiliary role. The regulating ball valve on the main pipe plays a leading role as the main control executive element. The pressure-setting value of the non-switching channel and the main pipe is related to the voltage stabilization effect of the MCCS system. The specific method is as follows: adjust the switching time of the switching branch valve to make the switching waveform a convex pressure wave, so that the pressure-setting value can be set as large as possible (that is, the pressure when the three channels are normally collected and supplied); secondly, record a set of pressure data in the pipeline when the water supply is stable before switching, and calculate the average value; finally, the average value is used as the pressure-setting value of the switching process in this pipeline.

4. Results and Discussion

4.1. Simulation Result Analysis

By using the co-simulation platform, the control process of the multi-channel concentrated liquid supply system is simulated, and the feasibility of the co-simulation platform and control scheme is verified through step response, sinusoidal tracking and anti-interference, respectively. In addition, in this simulation analysis, a traditional PID and an adaptive fuzzy PID controller are used as comparison methods to study the change in the main pipe’s pressure after clustering, and explain the advantages of a variable universe fuzzy PID controller in the control of MCCS system. In order to facilitate the comparison and analysis, we use a set of PID parameters with better control effects ($K_p = 4.5, K_i = 3.4, K_d = 10, T = 0.05 s$) while the rest of the basic parameters are exactly the same, and the control effect of three controllers is observed under different target signals.
4.1.1. Step Response

Set channel 1, channel 2 and channel 4 of the MCCS system to work, load the simulation ball valve opening to 100% with no interference, and only open the main controller. The set value of the pressure in the main pipe is set at a step from 0.025 MPa to 0.035 MPa, and the step response curve of the pressure in the main pipe is obtained, as shown in Figure 13. It can be seen from the figure that, when the set value of the main pipe changes in a step, the control effect of the MCCS system using the variable universe fuzzy PID is compared with the traditional PID control and adaptive fuzzy PID control, with a shorter adjustment time and higher control accuracy.

![Figure 13. Step response curve.](image1)

4.1.2. Sinusoidal Tracking Response

Set channel 1, channel 2 and channel 4 of the MCCS system to work, load the simulation ball valve opening at 100% with no interference, and only open the main controller. The main pressure-setting value is a sinusoidal signal with a frequency of 0.5 Hz and a varied range of [0.015, 0.035] MPa. The tracking effect is shown in Figure 14. The main pipe pressure under the three control methods has a certain lag and error. It can be seen from the figure that the changing trend of the tracking error also shows a sinusoidal trend. Moreover, the tracking error of the variable universe fuzzy PID control is compared with the tracking error of the adaptive fuzzy PID and the traditional PID, and is slightly smoother. It is proven that the variable universe fuzzy PID control has good dynamic characteristics and high tracking accuracy.

![Figure 14. Sinusoidal tracking response curve.](image2)
4.1.3. Anti-Interference Performance

There are a lot of interferences in the MCCS system that cause pressure changes in the main pipe, such as pressure changes caused by the centrifugal pump itself, valve jitter, water belt contraction and so on. In view of the accumulation characteristics of the MCCS system, the main pipe pressure fluctuation caused by the water source switching is also a factor that cannot be ignored. Set the load simulation ball valve opening to 100%; channel 1, channel 2 and channel 4 run in parallel, channel 3 is on standby. Switch between channel 2 and channel 3. The switching time for channel 2’s valve delays the start by 4 s and 10 s, respectively. The pressure value of the main pipe is set as 0.0392 MPa. According to the pressure of channel 1 before switching, the set pressure of channel 1 is 0.096 MPa. Then, at the same time, the system using different control methods is switched, and the real-time value of the main pipe’s pressure is recorded. The main pipe pressure change curves under the control of traditional PID, adaptive fuzzy PID, variable universe fuzzy PID and master and auxiliary composite control are obtained, as shown in Figure 15.

![Graphs showing anti-interference performance curves](image)

Figure 15. Anti-interference performance curve: (a) Delay time 4 s; (b) Delay time 10 s.

It can be seen from Figure 15 that, under the same switching conditions, compared with other controls, the main pipe’s pressure fluctuation value is smaller, and the recovery time to the set value is shorter. Therefore, the master and auxiliary composite control method based on the variable universe fuzzy PID has the stronger anti-interference ability, and is a more suitable smooth switching control strategy.

4.2. Experimental Verification

In addition to computer simulation experiments, in order to verify the effective application of the master and auxiliary composite control strategy proposed in this paper in the MCCS system, a physical test platform is built in the laboratory. In the experiment, the AMESim simulation model is replaced by a physical test platform, and the LabVIEW programming controller in the simulation model is modified. Combined with a National Instruments (NI) acquisition card and output card, a 4–20 mA analog quantity is used to simulate the signal of the field sensor and the control signal of the adjusting ball valve.

Through the co-simulation technology, the control parameters of the smooth switching process of the MCCS system are obtained, and are fine-tuned during the experiment process. Finally, the following control parameters are obtained: initial PID parameters $K_p^0 = 4.86$, $K_i^0 = 3.375$ and $K_d^0 = 11$; scale factor $K_{kp} = 0.5$, $K_{ki} = 0.7$ and $K_{kd} = 1.67$; quantization factor $K_e = 165$ and $K_{ec} = 40$. According to this parameter, the two-channel smooth switching is carried out in the test platform. The specific process is as follows: channel 1, channel 2 and channel 4 are connected in parallel for water supply, and channel 3 is in standby; after the start is stable, the pipeline pressures are set for the main pipe, channel 1 and
channel 4; the switch is started between channel 2 and channel 3, while channel 2 delays the switch 4 s. The opening degrees of the load simulation ball valve are 100%, 75% and 50%, respectively. Finally, the analysis experimental data are recorded, as shown in Figure 16 and Table 7.

![Figure 16](image-url)

**Figure 16.** Pressure change curve of main pipe with smooth switching under different loads: (a) Load simulation ball valve opening 100%; (b) Load simulation ball valve opening 75%; (c) Load simulation ball valve opening 50%.

| Load Simulation Ball Valve Opening | Set Valve/MPa | Maximum Deviation Rate |
|-----------------------------------|---------------|------------------------|
|                                   |               | No Control | Adaptive Fuzzy PID | Variable Universe Fuzzy PID | Master and Auxiliary Composite Control |
| 100%                              | 0.037         | 28.9%       | 22.4%             | 20%                          | 16.2%                                     |
| 75%                               | 0.05          | 26.4%       | 19.2%             | 16%                          | 8%                                        |
| 50%                               | 0.127         | 15.03%      | 9.05%             | 6.45%                        | 4.17%                                     |

**Table 7.** Maximum deviation rates of main pipe pressures of different control methods during the switching process.

The following points can be identified in Figure 16.

In different load simulations of the main pipe, adaptive fuzzy PID, variable universe fuzzy PID and master and auxiliary composite control can reduce the maximum deviation of the main pipe pressure, and the performance of the master and auxiliary composite control has a slight advantage. With the increase in the simulated load of the main pipe, the three control methods have improved the control of the deviation rate. This can be inferred from Table 7. However, the basic function of the
combined multi-channel concentrated water supply system is to superimpose the water supply and increase the water supply capacity. The simulated load of the main pipe cannot be too large, and the flow rate of the main pipe is lower than the flow rate provided before the aggregation.

Comparing the control effect of the same main pipe load (Figures 15a and 16a), it can be seen that the adaptive fuzzy PID, the variable universe fuzzy PID and the master and auxiliary composite control are not as good as the simulation result, that is, the controlled main pipe pressure fluctuation amplitude is higher than the simulation result. The main reason for this experimental result is the dead zone characteristics of the main control ball valve. When the input signal of the main control valve changes a little, the actuator may not act. In this way, when the output of the controller is small, the opening of the main electric valve cannot be corrected in time, resulting in a large amplitude of pressure fluctuation in the main pipe. On the other hand, when the controller parameter settings are more sensitive, the control system is prone to frequent fluctuations. Therefore, in order to avoid frequent fluctuations in the control system, the controller parameters should be set reasonably.

From the analysis of the control response time, the response time of the master and auxiliary composite control is obviously lower than that of adaptive fuzzy PID and variable universe fuzzy PID control. Under the same switching fluctuation, the passing time is shorter, and the response speed is faster.

The pipeline pressure control is common, but the research on pressure control in the MCCS system for fire-fighting is comparatively sparse. This paper demonstrates an exhaustive study of the variable universe fuzzy PID controller. Furthermore, the auxiliary controller of the branch pipeline is considered based on the dynamic characteristics of the switching process of the MCCS system. Therefore, a thorough study of the control strategy based on the master and auxiliary composite is illustrated for the main pipe pressure change. Additionally, the valve controller and pressure set point coordinated controller are added to the control strategy so as to apply the switching conditions. Traditional PID, single fuzzy PID and variable universe fuzzy PID can also realize the control of main line pressure. However, the outcomes reveal that the overall performance of the master and auxiliary composite control strategy is superior. The main pipe pressure control studies are examined under different delay times and different loads of the MCCS system. It is observed from the simulation and experiment results that the main pipe pressure with the proposed control strategy achieves excellent outcomes.

5. Conclusions

This paper analyzes the mathematical model of the MCCS system, and establishes a simulation model based on AMESim. According to the application scenario of the MCCS system, a master and auxiliary composite control strategy with variable universe fuzzy PID as the primary control is proposed, a co-simulation platform based on LabVIEW and AMESim is built, and the master and auxiliary composite controller is designed. Combining simulation and experimental testing, the following conclusions are obtained.

By comparing the data of the experiment and the simulation model, the accuracy of the AMESim model is verified from the two aspects of the constant flow and the unsteady flow of the MCCS system.

The main controller’s precision and adaptive ability are improved by using the idea of the variable theory domain. A master and auxiliary composite control strategy is proposed, which further increases the anti-interference ability of the control system, especially the peak clipping ability of the pressure peak caused by the common switching condition of the MCCS system.

According to the co-simulation technology, a co-simulation platform based on LabVIEW and AMESim is built, which can realize the switching of working conditions, the pressure adjustment of each channel, the setting of control parameters, and the data acquisition, processing and storage. It has good operability and an excellent human–computer interaction interface. Through the analysis and comparison of different control schemes, the effectiveness of the main and auxiliary compound control
strategies is verified, and the controller parameter values are initially obtained, which reduces the workload of subsequent tests.

The experimental results showed that compared with adaptive fuzzy PID and variable universe fuzzy PID control methods, the main and auxiliary compound control strategy has a strong anti-interference ability, a fast dynamic response speed, high stability and a good peak shaving effect.

The results presented in this work can be used to guide the design and operation of the control system of the MCCS device, meet the stable and continuous requirements of the water supply system, and improve the efficiency of fire water supply. Of course, the research in this paper has certain limitations. The proposed master and auxiliary composite control strategy is only for pressure fluctuations caused by switching operating conditions. The next research direction of this paper will continue to improve the control scheme and expand its applicable working conditions.

Author Contributions: Conceptualization, G.Z. and W.L.; methodology, G.Z.; software, G.Z.; validation, G.Z., J.W., J.Z. and W.L.; formal analysis, G.Z.; investigation, G.Z.; resources, J.W. and W.L.; data curation, G.Z.; supervision, J.W. and W.L.; project administration, J.W. and W.L.; funding acquisition, W.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research work was supported by National Key R&D Program of China, grant number 2016YFC0802900, and a Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions, Top-notch Academic Programs Project of Jiangsu Higher Education Institutions.

Conflicts of Interest: The authors declare no conflict of interest.

References
1. Schmitt, C.; Pluvinage, G.; Hadj-Taieb, E.; Akid, R. Water pipeline failure due to water hammer effects. Fatigue Fract. Eng. Mater. Struct. 2006, 29, 1075–1082.
2. Chen, T.; Ren, Z.; Xu, C.; Loxton, R. Optimal boundary control for water hammer suppression in fluid transmission pipelines. Comput. Math. Appl. 2015, 69, 275–290.
3. Jallouf, S.; Schmitt, C.; Pluvinage, G.; Hadj-Taieb, E.; Lébienvenu, M. A probabilistic safety factor for defect assessment of water pipes subjected to water hammer. J. Strain Anal. Eng. Des. 2011, 46, 14–26.
4. Ramos, H.; Tamminen, S.; Covas, D. Water supply system performance for different pipe materials Part II: Sensitivity analysis to pressure variation. Water Resour. Manag. 2009, 23, 367–393.
5. Zhao, G.; Li, W.; Zhu, J. A numerical investigation of the influence of geometric parameters on the performance of a multi-channel confluent water supply. Energies 2019, 12, 4354.
6. Feng, H.; Yin, C.B.; Weng, W.W.; Ma, W.; Zhou, J.J.; Jia, W.H.; Zhang, Z.L. Robotic excavator trajectory control using an improved GA based PID controller. Mech. Syst. Signal Process. 2018, 105, 153–168.
7. Moradi, H.; Saffar-Avval, M.; Bakhtiari-Nejad, F. Sliding mode control of drum water level in an industrial boiler unit with time varying parameters: A comparison with H∞-robust control approach. J. Process Control 2012, 22, 1844–1855.
8. Wu, X.; Shen, J.; Li, Y.; Lee, K.Y. Fuzzy modeling and stable model predictive tracking control of large-scale power plants. J. Process Control 2014, 24, 1609–1626.
9. Liu, C.; Zhao, J.; Gu, J.; Du, Y.; Li, Z.; Zhu, Z.; Mao, E. Pressure control algorithm based on adaptive fuzzy PID with compensation correction for the tractor electronic hydraulic hitch. Appl. Sci. 2020, 10, 1–17.
10. Liang, H.; Zou, J.; Zuo, K.; Khan, M.J. An improved genetic algorithm optimization fuzzy controller applied to the wellhead back pressure control system. Mech. Syst. Signal Process. 2020, 142, 106708.
11. Wang, C.; Xu, L.; Xu, M.; Yao, C.; Huang, H. Design and experimentation of grouting pressure automatic control system. Chin. J. Nonferrous Met. 2013, 23, 2704–2711.
12. Wang, B.Q.; Han, X.; Zhang, C.; Zhou, Y. Simulation on Fuzzy Control of Steam Temperature for a Lignite-Fired Boiler. J. Eng. Thermophys. 2017, 38, 27–32.
13. Zeng, W.; Jiang, Q.; Xie, J.; Yu, T. A functional variable universe fuzzy PID controller for load following operation of PWR with the multiple model. Ann. Nucl. Energy 2020, 140, 107174.
14. Zhang, L.; Cao, A.; Du, Y. Variable universe fuzzy control for excitation system of HTS machine. J. Intell. Fuzzy Syst. 2015, 29, 2457–2465.
15. Cao, Z.; Zheng, S. MR-SAS and electric power steering variable universe fuzzy PID integrated control. Neural Comput. Appl. 2019, 31, 1249–1258.

16. Ma, Z.; Zhao, Y.; Wang, J. The research of course control based on variable universe fuzzy PID. In Proceedings of the 5th International Conference on Mechatronics and Robotics Engineering, Rome, Italy, 16–19 February 2019; pp. 88–92. [CrossRef]

17. Song, L.; Huang, J.; Liang, X.; Yang, S.X.; Hu, W.; Tang, D. An intelligent multi-sensor variable spray system with chaotic optimization and adaptive fuzzy control. Sensors 2020, 20, 1–23.

18. Zeng, S.; Shi, Z.; Wang, P.; Zhang, G. Dynamic simulation of control for main steam pressure of marine steam power system. CIESC J. 2016, 67, 334–340.

19. Orlowska-Kowalska, T.; Kamiński, M.; Szabat, K. Implementation of a sliding-mode controller with an integral function and fuzzy gain value for the electrical drive with an elastic joint. IEEE Trans. Ind. Electron. 2010, 57, 1309–1317.

20. Zhang, B.; Peng, M.; Cheng, S.; Sun, L. Novel fuzzy logic based coordinated control for multi-unit small modular reactor. Ann. Nucl. Energy 2019, 124, 211–222.

21. Anderson, J.D. Governing Equations of Fluid Dynamics, 3rd ed.; Springer: Berlin/Heidelberg, Germany, 2009; pp. 15–51.

22. Olszewski, P. Genetic optimization and experimental verification of complex parallel pumping station with centrifugal pumps. Appl. Energy 2016, 178, 527–539. [CrossRef]

23. Chern, M.J.; Wang, C.C.; Ma, C.H. Performance test and flow visualization of ball valve. Exp. Therm. Fluid Sci. 2007, 31, 505–512. [CrossRef]

24. Bracco, R.; Clemente, S.; Micheli, D.; Reini, M. Experimental tests and modelization of a domestic-scale ORC (Organic Rankine Cycle). Energy 2013, 58, 107–116. [CrossRef]

25. Li, A.; Liu, X.; Chen, W. A variable universe fuzzy control algorithm based on fuzzy neural network. In Proceedings of the World Congress on Intelligent Control and Automation (WCICA), Chongqing, China, 25–27 June 2008; pp. 453–457.

Publisher’s Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.