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An Experimental Study on the Flow Characteristics of Electric Control Ball Valves and the Energy Saving Effects of Variable-Frequency Water Pumps in Building Central Heating Systems

Xiyao Li [1], Xunjie Gan [2], Changhong Zhan [1,*], Yongjie Wang [3,*], Yunhai Li [4,*], Wenbin Zhang [5] and Yimeng Feng [6]

1 School of Architecture and Design, Harbin Institute of Technology; Key Laboratory of Cold Region Urban and Rural Human Settlement Environment Science and Technology, Ministry of Industry and Information Technology, Harbin 150001, China
2 Beijing Zhenxing Institute of Metrology and Measurement, Beijing 100074, China
3 Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen 518055, China
4 School of Robotics and Advanced Manufacture, Harbin Institute of Technology (Shenzhen), Shenzhen 518055, China
5 Nottingham Trent University, School of Science and technology, 50 Shakespeare St, Nottingham NG1 4FQ, UK
6 Department of Architecture (DA), University of Bologna, 40136 Bologna, Italy
* Correspondence: zhan.changhong@hit.edu.cn (C.Z.); wangyongjie@sz.tsinghua.edu.cn (Y.W.); liyunhai@hit.edu.cn (Y.L.)

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Abstract: Central heating systems typically exhibit high energy consumption and carbon emissions. Within these networks, the flow characteristics of electric control ball valves are critical for precise thermal regulation. Theoretical research on this topic is already extensive. However, further investigation through field tests is needed to elucidate both the intrinsic flow behaviors of these valves and their coupling with proportional-integral-derivative (PID) control, as well as the energy efficiency comparison between variable-frequency water pumps and valve-based modulation. Therefore, a semi-physical smart heating simulation and experimental platform was proposed, and corresponding field tests were conducted. The valve was subsequently applied to both household-level room temperature regulation and building mean room temperature regulation, and the room temperature responses under various PID parameter settings were also evaluated. The research results indicate that when the opening degree of the electric control ball valve is within the range of 10% to 60%, the valve can maintain sufficient regulation sensitivity. For household-level room-temperature regulation, increasing the proportional gain from P = 10 to P = 20 under proportional-only control accelerated the thermal response and shortened the room-temperature rise process. At P = 10, introducing the integral action prolonged the rise time, while the addition of derivative action further delayed the thermal response, with a larger derivative parameter producing a more pronounced damping effect. For building-level mean room-temperature regulation, the heating response was relatively rapid, whereas the cooling process exhibited a slower and asymmetric temperature decay due to the thermal inertia of the tested building. Compared with valve opening modulation, variable-frequency operation reduces pump input power by 60.12%, whereas valve opening modulation yields only a 7.19% reduction. It indicates that regulating flow by adjusting pump frequency is more energy-efficient than relying only on valve opening modulation under the tested operating conditions. These findings provide a practical basis for the efficient operation and optimization of central heating systems.

Keywords: building; central heating system; electric control ball valves; PID; pump; variable-frequency

1. Introduction

Global energy is facing a severe crisis, within which building energy consumption accounts for a significant portion of total social energy consumption [1,2]. Moreover, heating systems in buildings represent a considerable share of this energy use [3]. Consequently, enhancing the energy efficiency of central heating systems is recognized as a critical pathway for reducing building-related emissions. In practice, complex hydraulic and thermal dynamics are inevitably encountered during the operation of these systems. Deviations between design specifications and actual operating conditions, coupled with uncertainties in pipe network resistance, variations in building envelope thermal performance, and fluctuating outdoor environments, frequently lead to hydraulic imbalances and thermal instability in central heating systems.

To address these challenges, the characteristics of terminal control valves in the central heating system and the practical energy-saving efficiency of variable-frequency pumps must be comprehensively evaluated. In current research, some studies have focused on developing new flow control valves and investigating their characteristics. Bao [4] proposed a novel ball valve equipped with a Savonius rotor, however, experimental measurements of its flow regulation characteristics are lacking. Other studies have prioritized the hydraulic and energy characteristics of valves. Specifically, Zhao [5] systematically analyzed the influence of control valve parameters on dynamic responses regarding the supply water temperature fluctuations of the secondary pipeline network, finally establishing an optimal parameter matching scheme for bypass control valves and heat exchange control valves. Si [6] investigated the effect of valve opening degrees on flow field characteristics, with results indicating a significant flow rate increase within the 30–40% opening range. Zhang [7] demonstrated that the process of energy loss and recovery is more symmetrical, and the flow structure is more stable at an 80% opening. Valve control algorithms have similarly been extensively investigated. Trica [8] proposed a multi-loop PID optimization strategy. Santos [9] proposed a multi-input multi-output PID controller to enhance the stability and robustness of the control system. Despite these advances, experimental evidence on the measured flow behaviour of commonly used terminal heating control valves remains limited. Moreover, the influence of the measured nonlinear valve characteristics on PID-based room-temperature regulation has not been sufficiently examined.

On the other hand, central heating systems are transitioning from traditional, steady-state operations toward dynamic, refined, and smart regulation. As an important component of the central heating system, the energy-saving efficiency of pumps is particularly crucial for the overall energy conservation of the system. Although variable-frequency water pump technology possesses substantial theoretical energy-saving potential, its practical benefits under in-situ working conditions require further validation in comparison with the energy-saving effects of valve control [10]. For instance, Housh [11] proposed an energy-saving localized control strategy for variable-speed pump stations, demonstrating a reduction in energy consumption of approximately 10%, but the comparison of its energy-saving effects with valve control was not clearly specified. Shi [12] proposed a motor control strategy, and results indicate that the proposed strategy has good performance. But the research focus is placed on system robustness analysis. Wang [13] pointed out that the power of a pump in the heating, ventilating and air conditioning system can respond rapidly to frequency changes, while the flow rate response is slightly slower.

To address the above specific issues, a semi-physical smart heating simulation and experimental platform for evaluating the hydraulic-control and energy-saving characteristics of building central heating systems was proposed. Utilizing this platform, the flow characteristics of a common used electric control ball valve were empirically measured across various opening degrees. Compared with studies that examine valve characteristics, control performance, or pump operation separately, the present work provides an integrated experimental evaluation of terminal valve behavior, PID-based thermal regulation, and pump energy-saving performance on the same platform. The main contributions of this study are as follows: (1) a semi-physical experimental platform covering the source-network-load-storage process of a central heating system was constructed to reproduce practical hydraulic and thermal regulation processes; (2) the flow characteristics of a commonly used electric control ball valve were experimentally measured, and its effective regulation range was identified under heating-system operating conditions; (3) the influence of the measured nonlinear valve-flow characteristic on PID-based room-temperature regulation was examined at both household and building levels; and (4) the practical energy-saving effect of variable-frequency pump operation was directly compared with valve-based flow modulation.

These contributions provide experimental evidence for valve selection, PID parameter regulation, and pump operation optimization in smart central heating systems.

2. Materials and Methods

2.1. The Semi-Physical Smart Heating Simulation and Experimental Platform

A semi-physical smart heating simulation and experimental platform was designed and constructed. The platform comprehensively covers the entire physical process of the source-grid-load-storage components in a central heating system. It consists of two core modules: a semi-physical model and a computer simulation and experimental management platform, which facilitate real-time communication and data exchange. The semi-physical model includes the primary network, secondary network, and heat exchange stations. A photograph of the physical experimental platform is shown in Figure 1.

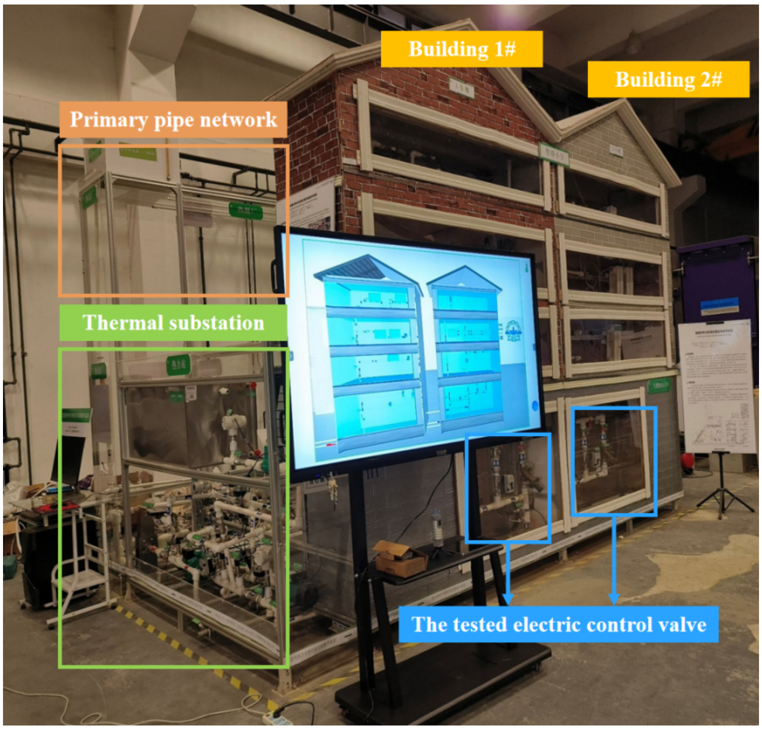


Figure 1. The semi-physical smart heating simulation and experimental platform.

Both the primary and secondary networks in the experimental platform are configured with two system layouts: series-connected pumps and parallel-connected pumps. In the secondary network, Building #1 employs a two-pipe radiator heating system. Each room (e.g., 1#101, 1#201, 1#301) is equipped with a room temperature sensor, an electric control ball valve, and a heat meter. Building #2 utilizes a single-pipe radiator heating system, with room temperature sensors also installed in each room. At the building heat inlets of both Building #1 and Building #2, electric control ball valves for regulation and heat meters for measurement are installed. Furthermore, the terminal devices of the experimental platform transmit signals to the electrical control cabinet via wired connections. The electrical control cabinet is configured with a programmable logic controller system for control purposes.

2.2. Flow Characteristic Test of the Electric Control Ball Valves

The electric control ball valve, commonly used in field applications, is selected by this study for investigation. The electric control ball valve, serving as the core underlying physical actuator in a central heating system, directly determines the accuracy with which the system translates control algorithms (e.g., PID control) into actual hydraulic condition distribution. The flow characteristic of a valve refers to the relationship between the relative flow rate (the ratio of the flow rate G at a certain opening to the full-open flow rate G_max) and the relative opening (the ratio of the stroke at a certain opening to the stroke at full opening) of the medium flowing through it.

The selected test subjects are the electric control ball valves installed at the building heat inlets of Building #1 (Electric Control Ball Valve 1) and Building #2 (Electric Control Ball Valve 2). The flow rates were measured by the heat meters installed at the corresponding building heat inlets, and the valve openings were set via the supporting software system. During the flow-characteristic tests, the supply water temperature was maintained at 45.00 ± 0.5 °C. The temperature directly affects the kinematic viscosity of the working fluid, thereby influencing the Reynolds number and the internal flow regime within the valve. To improve the reliability of the experimental results and reduce the influence of random hydraulic fluctuations, the experimental was repeated 4 times. The set experimental conditions are listed in Table 1.

The hydraulic boundary conditions of the two tested valves were further clarified. Electric Control Ball Valve 1 and Electric Control Ball Valve 2 were installed at the heat inlets of Building #1 and Building #2, respectively. During the flow-characteristic tests, the pump operating frequency, main-network configuration, and other branch-valve states were maintained unchanged to reduce variations in system resistance. Therefore, the comparison of the two valve curves was interpreted under the steady condition.

To quantitatively characterize the flow-regulation performance of the tested electric control ball valves, the measured flow rate and valve opening were first normalized. The relative flow rate $q_{r,i}$ and relative valve opening $l_{r,i}$ at the (i)th test point were calculated as follows:

$$q_{r,i} = \frac{G_i}{G_{\max}} \tag{1}$$

$$l_{r,i} = \frac{L_i}{L_{\max}} \tag{2}$$

where $q_{r,i}$ is the dimensionless relative flow rate at the (i)th test point, G_i is the measured volumetric flow rate at the corresponding valve opening, m^3/h; G_{max} is the measured volumetric flow rate at the fully open position, m^3/h; $l_{r,i}$ is the dimensionless relative valve opening at the (i)th test point; L_i is the valve opening at the (i)th test point; and $L_{\max}$ is the fully open valve position, corresponding to 100% opening.

The local flow gain K_i between two adjacent test points was defined as the average slope of the relative flow rate–relative valve opening curve over the corresponding opening interval:

$$K_i = \frac{q_{r,i+1} - q_{r,i}}{l_{r,i+1} - l_{r,i}} \tag{3}$$

where K_{i} is the dimensionless local flow gain between the (i)th and (i + 1)th test points; $q_{r,i}$ and $q_{r,i+1}$ are the relative flow rates at two adjacent test points; and $l_{r,i}$ and $l_{r,i+1}$ are the corresponding relative valve openings. A larger K_i indicates that a given change in valve opening produces a greater relative flow-rate response and, therefore, a higher local flow sensitivity.

To further quantify the proportion of the total available flow-rate variation occurring within a specified valve-opening interval, a flow-variation contribution ratio C_{a-b} was defined in this study as

$$C_{a-b} = \frac{q_r(b) - q_r(a)}{q_r(100\%) - q_r(0\%)} \times 100\% \tag{4}$$

where C_{a-b} is the percentage contribution of the opening interval from (a) to (b) to the total available relative flow-rate variation; (a) and (b) are the lower and upper limits of the specified valve-opening interval, respectively; $q_r(a)$and $q_r(b)$ are the relative flow rates at openings (a) and (b), respectively; and $q_r(0\%)$ and $q_r(100\%)$ are the relative flow rates at the fully closed and fully open positions, respectively. A larger C_{a-b} indicates that a greater proportion of the total flow-regulation capacity is concentrated within the specified opening interval.

Table 1. Setting of Experimental Conditions for the Electric Control Ball Valve Flow Characteristic Tests.

Case	Valve Opening	Case	Valve Opening
1	0%	5	60%
2	10%	6	80%
3	20%	7	100%
4	40%		

Basic Information of the electric ball valves used in the tests is shown in Table 2. Parameters of the ultrasonic heat meter used are shown in Table 3.

Table 2. Basic Parameters of the Tested Electric Control Ball Valve.

Parameter	Value	Prototype
Dimension	DN40	
Characteristic Curve	Percentage	
Drive Method	Electric	
Operating Temperature	2~94 °C	
Closing Pressure Difference	600 kPa	

Table 3. Parameters of the Heat Meter.

Parameter	Value	Prototype
Dimension	DN40	
Type	7743086081	
Accuracy	Level 2	
Flow Range	0.06–12 m^3/h	
Temperature Measurement Range	5~105 °C	

2.3. Regulation Characteristic Test of the Electric Control Ball Valves Based on PID Control

The PID controller calculates the control output based on the system error (the difference between the setpoint and the measured value) using proportional (P), integral (I), and derivative (D) actions. In this experiment, the room temperature control for unit 1#301 and the mean room temperature control for Building #2 were selected as the test conditions to examine the PID control characteristics of the electric proportional control method. During the testing process, the room temperatures of unit 1#301, and units 2#101, 2#201, and 2#301 in Building #2 were monitored. The experimental conditions are listed in Table 4.

Table 4. Regulation Characteristic Test of the Electric Control Ball Valves Based on PID Control.

Cases	Description	Test Object	Cases	Description	Test Object	PID Parameters
1	P = 10, I = 1, D = 0	Electric Control Ball Valve for Unit 1#301	4	Mean Room Temperature Setpoint 24 °C	Electric Control Ball Valve at the Thermal Entrance of Building #2	P = 10, I = 1, D = 0
2	P = 10, I = 0, D = 0		5	Mean Room Temperature Setpoint 25.5 °C		
3	P = 20, I = 0, D = 0					
4	P = 10, I = 1, D = 1					
5	P = 10, I = 1, D = 10					

Before the formal PID regulation tests, a series of preliminary tuning experiments were conducted on the semi-physical smart heating simulation and experimental platform to determine suitable PID parameter combinations. The tested heating system is characterized by thermal inertia, response delay, and nonlinear valve-flow behavior; therefore, the PID parameters were not directly determined using a conventional tuning rule such as the Ziegler–Nichols method. Instead, they were obtained through repeated experimental calibration under the operating conditions of the present platform.

During the preliminary calibration process, different proportional, integral, and derivative parameter combinations were evaluated by comparing the room-temperature rise time, temperature fluctuation, overshoot tendency, valve-actuation stability, and the ability of the system to approach the target temperature. Based on these comparative tests, the PID parameter combinations listed in Table 4 were selected for the formal experiments because they produced more stable and effective temperature regulation performance in the tested heating system. Therefore, the selected PID parameters reflect experimentally optimized control settings for the present semi-physical heating platform.

The electric control ball valve used for testing in unit 1#301 shares the same basic parameters as those listed in Table 2, except that the valve size was replaced with DN20. The basic information for the room temperature sensors used in the temperature tests is provided in Table 5.

Table 5. Parameters of the Room Temperature Sensors.

Parameter	Value	Prototype
Dimension	DS18B20	
Range	−55 °C~125 °C	
Error	±0.2 °C	

2.4. Energy-saving Effect Test of Variable-frequency Pump Operation

To account for differences in flow rate among the tested operating conditions, the specific electrical energy consumption per unit water volume (SEC) was introduced as a normalized energy-performance indicator and calculated as follows:

$$SEC = \frac{P_{in}}{Q} \quad (5)$$

where *SEC* is the specific electrical energy consumption, kWh/m^3; P_{in} is the measured motor input power, kW; and *Q* is the measured volumetric flow rate, m^3/h. A lower *SEC* indicates lower electrical energy consumption for transporting a unit volume of circulating water.

The secondary network pipeline was selected for conducting experiments to analyze the energy-saving effect of variable-frequency pump operation. Three operational cases were established to test the energy-saving performance of the variable-frequency pump. The case settings are listed in Table 6. Cases 1 and 2 were used to compare the pump energy consumption states when regulating the system flow under constant frequency conditions, while Cases 1 and 3 were used to compare the energy consumption between variable frequency operation and fixed frequency operation of the pump, respectively.

Table 6. Experiment on the Energy-saving Effect Test of Variable Frequency Pump Operation**.**

Cases	Description
1	Constant Frequency (50 Hz), Pump Outlet Valve Opening 100%
2	Constant Frequency (50 Hz), Pump Outlet Valve Opening 50%
3	Variable Frequency Operation (30 Hz)

During the testing process, the pump inlet and outlet pressures were monitored using pressure gauges, the electrical power consumption of the pump was measured with an electricity meter, and the pump flow rate was monitored using an ultrasonic heat meter. The parameters of the instruments employed for testing are listed in Table 7. The parameters of the ultrasonic heat meter are provided in Table 3.

Table 7. Instruments Used in the Energy-saving Effect Test of Variable-frequency Pump Operation**.**

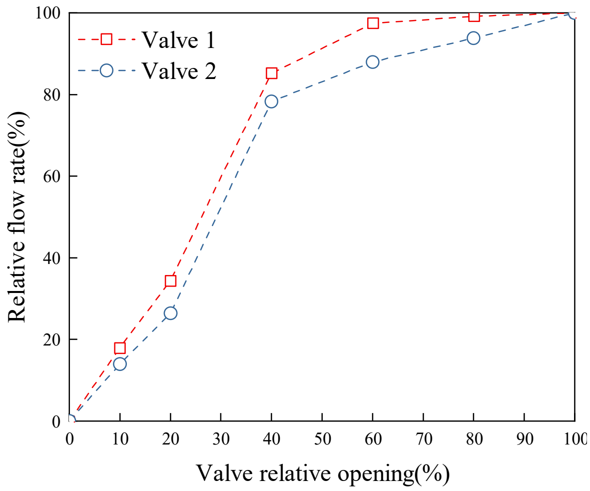
Name	Parameter	Value	Prototype
Pressure Gauge	Type	WT3620	
	Range	0–600 kPa	
Electric Meter	Communication Method	RS485	
	Current and Voltage Accuracy	0.2	
	Active Electric Energy	0.5	
Pump	Type	PUN402-EH	
	Rated Head	15 m	
	Rated Flow	50 L/min	

Based on the experimental results, the pump shaft power, effective power, and overall efficiency were calculated respectively.

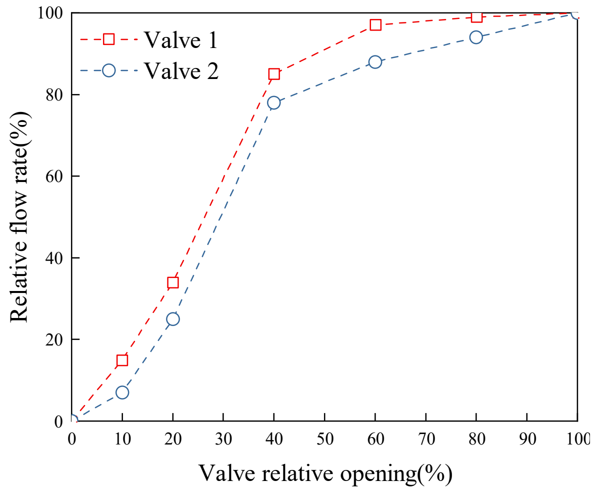
3. Results and Discussion

3.1. Flow Characteristic Test Results of the Electric Control Ball Valves

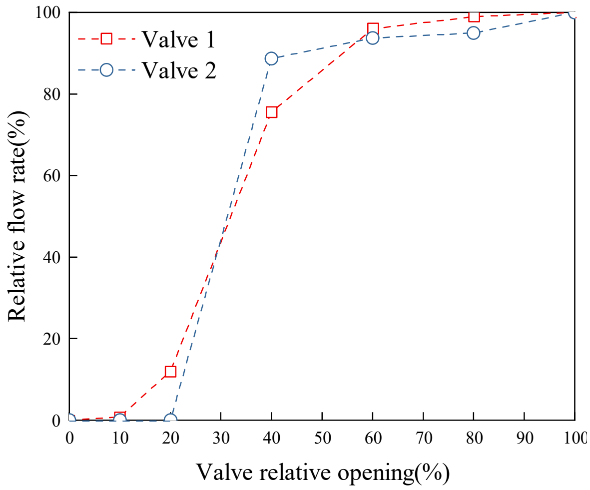
Figure 2 presents the relative flow characteristics of the two electric control ball valves obtained from four independent tests. The four experiments exhibited consistent overall trends, confirming the repeatability of the measured nonlinear valve-flow characteristics. At openings below 10%, both valves maintained relatively low flow rates, indicating that changes in valve opening produced only limited hydraulic responses in the low-opening region. In contrast, most of the available flow-rate variation occurred between 10% and 60% opening, during which the relative flow rates increased rapidly from low levels to approximately 90% or higher. When the valve opening exceeded 60%, the relative flow rates were already close to their maximum values, and further increases in valve opening resulted in only limited additional flow.



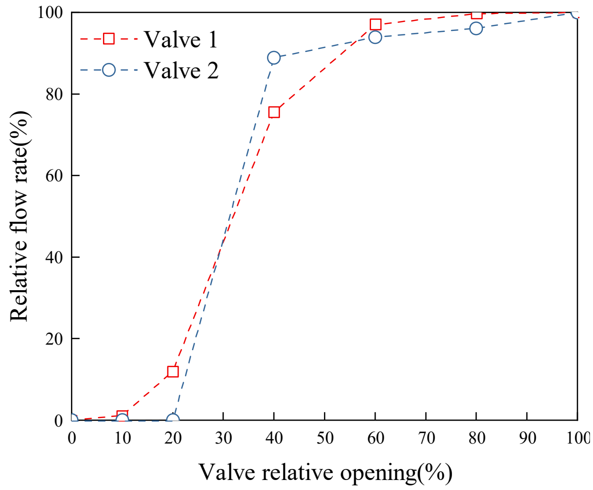
(**a**) The first test



(**b**) The second test



(**c**) The third test



(**d**) The fourth test

Figure 2. Flow Characteristic Curves of the Electric Control Ball Valves.

Although minor differences in relative flow rate were observed among the four independent tests, particularly within the intermediate-opening region, the overall nonlinear response patterns of both valves remained consistent. The repeated experimental results therefore indicate that the observed flow-characteristic trends were reproducible and were not determined by a single experimental realization. Based on the four independent tests, the 10–60% opening interval was identified as the main active regulation range of the tested electric control ball valves, because the majority of the effective flow-rate variation was concentrated within this interval.

The local flow-gain analysis provides further quantitative evidence of the nonlinear flow characteristics of the two tested valves. Taking Test 1 as an example, the calculated K_i values of Valve 1 for the 0–10%, 10–20%, 20–40%, 40–60%, 60–80%, and 80–100% opening intervals were 1.800, 1.640, 2.538, 0.615, 0.083, and 0.044, respectively. For Valve 2, the corresponding K_i values were 1.400, 1.238, 2.597, 0.481, 0.297, and 0.307, respectively. The maximum local flow gains of Valve 1 and Valve 2 were 2.538 and 2.597, respectively, and both occurred within the 20–40% opening interval. Therefore, the greatest local flow sensitivity was observed within this intermediate-opening interval.

The flow-variation contribution ratio further characterizes the distribution of the available flow-regulation capacity over the valve-opening range. For Valve 1, the C_{10-60} value was 79.47%, indicating that approximately four-fifths of the total available flow-rate variation occurred between 10% and 60% opening. The corresponding C_{10-60} value for Valve 2 was 73.93%. By contrast, the C_{60-100} values of Valve 1 and Valve 2 were only 2.54% and 12.07%, respectively. Thus, further increasing the valve opening above 60% produced a substantially smaller marginal flow-rate response.

These quantitative results distinguish the main active regulation range from the region of maximum local flow sensitivity. The 10–60% opening interval can be regarded as the main active regulation range because 73.93–79.47% of the total available flow-rate variation was concentrated within this range in Test 1. However, the maximum K_i values occurred specifically within the 20–40% opening interval. The pronounced variation in K_i

among the different opening intervals also confirms that the relationship between valve opening and flow rate is strongly nonlinear rather than constant-gain.

The observed nonlinear flow-response pattern is generally consistent with previous studies reporting that valve-opening adjustments can produce markedly non-uniform changes in flow rate. For example, Si [6] identified a significant increase in flow rate within the 30–40% opening range, indicating that intermediate valve openings may exhibit substantially higher flow sensitivity than other operating regions. A similar tendency was observed in the present four repeated tests, in which relatively steep increases in relative flow occurred over specific intermediate-opening intervals. However, the present results further show that the local flow gain is not uniform throughout the entire 10–60% interval. Therefore, this range should be interpreted as the main active regulation range, in which most of the available flow-rate variation is concentrated, rather than as a linear or constant-gain operating region.

Zhang [7] reported a more stable flow structure at an 80% opening for a butterfly valve under choked-flow conditions. In contrast, the tested electric control ball valves in the present heating system had already reached approximately 90% or more of their maximum relative flow by an opening of around 60%, after which the marginal increase in flow became limited. This difference is likely associated with the different valve structures and operating conditions considered in the two studies. The comparison therefore highlights the importance of experimentally characterizing the actual terminal valve used in a heating system rather than directly applying flow-characteristic conclusions obtained for other valve types.

3.2. Test Results of the Electric Control Ball Valve Regulation Characteristics Based on PID Control

Before the PID regulation tests, the heating system was operated until the hydraulic and thermal conditions reached a steady operating state. At the beginning of the household-level room-temperature regulation test for unit 1#301 shown in Figure 3, the supply and return water temperatures were 37.90 °C and 36.00 °C, respectively. At the beginning of the building-level mean room-temperature regulation test for Building #2 shown in Figure 4, the corresponding supply and return water temperatures were 32.25 °C and 31.78 °C, respectively. These initial temperatures were recorded to characterize the thermal boundary conditions at the start of the two PID regulation tests.

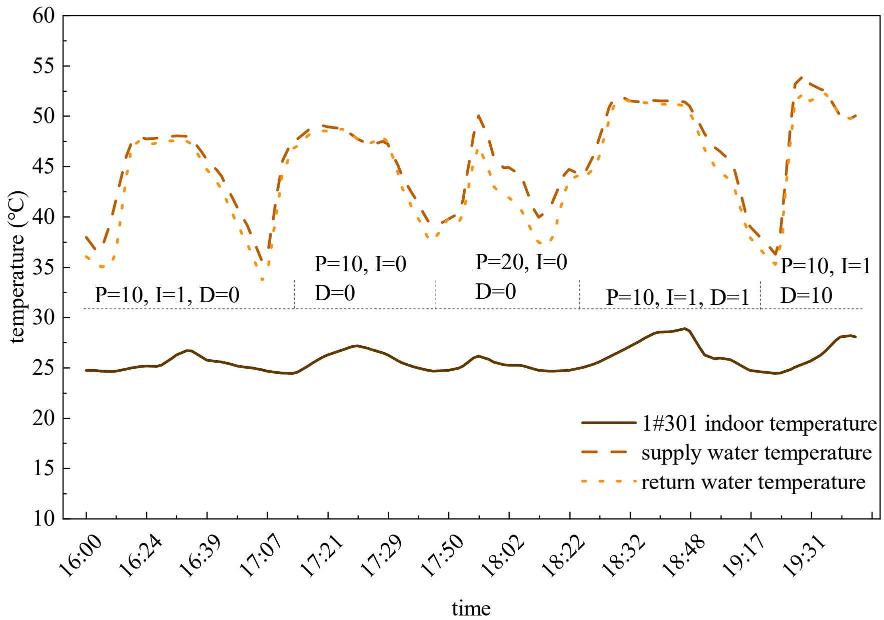


Figure 3. PID Control Results for the Room Temperature in Unit 1#301.

Figure 3 presents the PID control results for the room temperature in unit 1#301. The results indicate that after the I action was added to the P control, the rise time of the room temperature curve increased. A further addition of the D action resulted in an even longer response time for the room temperature. The reasons are as follows: with P-only control, the valve opening is proportional to the current temperature error. A larger error leads to a larger valve opening and thus faster heating. After adding the I action, the integral effect introduces a lag, causing the initial valve opening to be smaller than that with P-only control, which slows the room temperature rise. Furthermore, combined with the valve's flow characteristic curve, the relative flow rate is lower at small openings, resulting in weaker control effectiveness and a further extension of the rise time. When the D action is subsequently added, the derivative term, being sensitive to the rate of temperature change, suppresses the heating rate. This further delays the adjustment of the valve opening, leading to an even longer room temperature regulation time. Additionally, under P-only control, when the proportional gain P = 10, the valve action was slower compared to when P = 20, consequently resulting in a longer room temperature response time.

Figure 4 presents the PID regulation results for Building #2 under different target mean room temperature setpoints. The results show that under various mean room temperature setpoints, the response during the heating phase is consistently fast, with the PID control causing the valve to open rapidly, leading to a quick rise in room temperature. However, when the setpoint is lowered or the heating supply is stopped, the cooling process exhibits an asymmetric characteristic: in the initial stage, due to the large indoor-outdoor temperature difference, the heat dissipation rate is high, resulting in a relatively rapid decrease in room temperature; as the temperature difference diminishes, the heat dissipation gradually slows, causing the room temperature decline to level off.

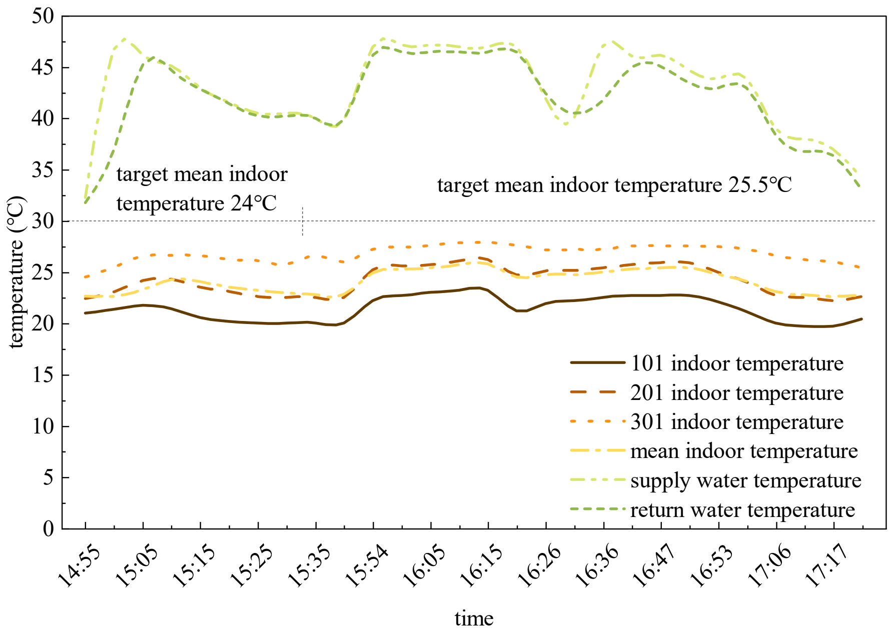


Figure 4. PID Control Results for Building #2.

Furthermore, as illustrated in Figure 2 to Figure 4, the measured nonlinear flow characteristic of the electrically controlled ball valve is a key factor influencing the PID regulation performance. Therefore, the effective control gain of the heating terminal is jointly determined by the PID parameters and the valve flow characteristic curve. When the valve operates in a low-gain region, a change in the control signal may lead to only a limited change in flow rate, thereby weakening the actual heating response and prolonging the room-temperature regulation time. Conversely, when the valve operates within the sensitive regulation range, the flow rate responds more effectively to valve-opening adjustments, allowing the PID controller to regulate the heat supply more efficiently. This indicates that PID parameter tuning should be considered together with the measured valve flow characteristic, rather than being treated as an independent control problem.

In addition, the indoor temperature response is influenced not only by valve actuation but also by the thermal inertia and time-delay characteristics of the heated room. After the valve opening changes, the resulting variation in water flow must first alter the heat release of the radiator and then be transferred to the indoor air and surrounding envelope surfaces. This multistage heat transfer process delays the observable room-temperature response. Consequently, excessive integral or derivative action may further slow the temperature adjustment, while an appropriate proportional gain can improve the initial response by increasing the effective valve actuation. These results indicate that the practical performance of PID-based heating control depends on the combined effects of valve flow nonlinearity, actuator response, and building thermal inertia.

Previous PID-related studies have mainly focused on controller formulation and tuning strategies. Trica [8] for example, developed a multi-loop PID tuning strategy, while Santos [9] investigated MIMO PID tuning to improve system stability and robustness. These studies demonstrate the importance of controller structure and parameter selection. The present results complement these control-oriented studies from the perspective of the physical actuator and thermal process. Specifically, the four repeated valve tests demonstrated that the relationship between valve opening and flow rate is strongly nonlinear. Consequently, an identical variation in the PID control output may produce different hydraulic responses depending on the operating region of the valve.

The room-temperature experiments further show that the thermal response is also affected by the inertia and time delay of the radiator-heated space. Therefore, the observed differences among the tested proportional, integral, and derivative settings cannot be attributed to the controller parameters alone. Rather, they result from the interaction among PID action, nonlinear valve-flow behavior, and the delayed building thermal response. This finding extends the discussion beyond controller tuning alone and emphasizes the need to consider the measured actuator characteristics when applying PID-based room-temperature regulation in central heating systems.

The supply and return water temperature curves were further included in Figures 3 and 4 to characterize the dynamic thermal input of the heating system during PID regulation. As shown in Figure 3, the supply and return water temperatures exhibit relatively rapid variations among the different PID-control stages, whereas the indoor temperature of unit 1#301 changes more gradually. A similar response pattern can be observed in Figure 4. Although the water temperatures vary markedly during the regulation process, the mean indoor temperature exhibits a smoother and delayed variation.

The difference in response rate reflects the multistage heat-transfer process of the radiator-heating system. Changes in the thermal condition of the circulating water first affect the heat release from the radiator, after which the heat is transferred to the indoor air and the surrounding building envelope. Owing to the thermal capacity of the radiator, indoor air, and envelope surfaces, the room-temperature response lags behind the variation in the supply and return water temperatures. Therefore, the indoor thermal response observed under different PID settings is governed not only by the controller parameters but also by the thermal inertia and heat-transfer delay of the heating system.

3.3. Energy-saving Performance Test Results of Variable-frequency Pump Operation

Table 8 presents the test data on the energy-saving effect of variable-frequency pump operation. The results indicate that variable-frequency pump operation achieves significant energy savings compared to regulating the valve opening. Case 2 shows only a 38 W (7.19%) decrease in input power compared with Case 1. Although the pump efficiency in Case 3 (with variable frequency operation) was similar to that in Case 2, its input power decreased from 491.00 W to 195.80 W (an energy reduction of 60.12%). Compared with full-opening constant-frequency operation, the reduction reached approximately 62.98%. After reducing the valve opening to 50% in Case 2, compared to the constant frequency operation in Case 1, the pump's effective power, efficiency, and input power all decreased. The reason is that closing the valve increases the system resistance, shifting the pump's operating point to the left and away from the high-efficiency zone, thereby reducing its efficiency. Notably, although the pump efficiencies in the three cases are relatively low and similar, this does not diminish the significance of the comparative energy-saving analysis across different operating conditions. On the contrary, it highlights that the substantial reduction in input power in Case 3 is primarily attributed to the reduced shaft power demand rather than an improvement in pump efficiency itself.

Table 8. Test Results of the Energy-saving Effect of Variable-frequency Pump Operation**.**

Pump Performance Parameter	**Heating System Operating Condition**		
	Case 1	**Case 2**	**Case 3**
Pump Inlet Pressure (kPa)	50.12	81.00	85.00
Pump Outlet Pressure (kPa)	206.19	274.00	150.00
Pressure Difference (kPa)	156.07	193.00	65.00
Flow Rate (m^3/h)	2.10	1.38	1.72
Motor Input Power (W)	529.00	491.00	195.80
Pump Shaft Power (W)	380.88	353.52	140.98
Pump Effective Power (W)	91.00	73.95	31.04
Pump Efficiency (%)	23.89	20.92	22.01

As the flow rates of Cases 1, 2, and 3 were 2.10, 1.38, and 1.72 m^3/h, respectively, a direct comparison of motor input power alone does not fully account for the differences in the hydraulic operating conditions. Therefore, the specific electrical energy consumption per unit water volume was further used to normalize the pump energy consumption.

The calculated SEC values were 0.252, 0.356, and 0.114 kWh/m^3 for Cases 1, 2, and 3, respectively. When the pump outlet valve opening was reduced from 100% to 50% at a constant frequency of 50 Hz, the motor input power decreased from 529.00 to 491.00 W, corresponding to a reduction of 7.19%. However, because the flow rate decreased from 2.10 to 1.38 m^3/h, the SEC increased by approximately 41.26%, from 0.252 to 0.356 kWh/m^3. This result indicates that valve throttling reduced the absolute electrical power demand but increased the electrical energy required to transport a unit volume of circulating water.

By contrast, the variable-frequency operating condition exhibited an SEC of 0.114 kWh/m^3, which was 67.97% lower than that of the valve-throttling condition in Case 2. The lower normalized energy consumption indicates that reducing the pump operating frequency is more energy-efficient than increasing hydraulic resistance through valve throttling under the tested conditions.

Previous studies have demonstrated the energy-saving potential of variable-speed pump operation in heating and building systems. Sarbu [10] evaluated the energy-saving potential of pumping regulation in district heating stations, while Housh [11] reported an energy-consumption reduction of approximately 10% using a localized variable-speed pump control strategy. Wang [13] further showed that pump power can respond rapidly to frequency changes, whereas the corresponding flow response is relatively slower. The present experimental results are consistent with the general conclusion that frequency regulation can substantially reduce pump input power.

Unlike studies primarily focused on variable-speed control strategies or pump dynamic responses, the study experimentally evaluated variable-frequency operation and valve-based modulation on the same semi-physical heating platform. Under the tested operating cases, reducing the valve opening from 100% to 50% at 50 Hz decreased the motor input power by 7.19%, whereas the 30 Hz variable-frequency case exhibited a substantially lower input power. This difference supports the hydraulic explanation that valve throttling mainly increases system resistance, while frequency reduction directly decreases pump power demand.

4. Conclusions

To facilitate the efficient regulation of central heating systems, an experimental platform integrating the comprehensive source-network-load-storage process was constructed. Utilizing this system, the flow characteristics of the terminal electric control ball valve and the PID control performance of the electric control ball valve, along with the energy-saving efficiency of a variable-frequency water pump, were tested. The principal conclusions are summarized as follows:

(1) Optimal regulatory sensitivity is achieved when the electric control ball valve opening is maintained between 10% and 60%, effectively avoiding the deadband phenomenon at low openings and saturation effects at high openings.

(2) When the electric control ball valve is utilized for both individual household temperature control and building-mean room temperature control, the indoor thermal response is tightly coupled with the configured PID parameters, which jointly determine the indoor temperature variation rules under the thermal property of the experimental building.

(3) Compared with valve opening modulation, variable-frequency operation reduces pump input power by 60.12%, whereas valve opening modulation yields only a 7.19% reduction. It indicates that regulating flow by adjusting pump frequency is more energy-efficient than relying only on valve opening modulation under the tested operating conditions.

These findings provide empirical operational data for the operation and control of central heating systems, offering practical guidelines for the selection of valves and pumps, the choice of operation control strategies, and overall system design. However, this study only tested the characteristics of a specific electric control ball valve and water pump. The characteristics of valves and pumps with more sizes remain to be investigated. Moreover, this study was conducted in a laboratory setting; further research is needed to carry out tests in actual buildings.

Author Contributions

X.L.: Methodology, Data collection, Writing—original draft. X.G.: Software, Writing-original draft. C.Z.: Project administration, Validation, Resources. Y.W.: Experimental study, Writing—Review & Editing. Y.L.: Supervision, Conceptualization. W.Z.: Supervision, Data processing. Y.F.: Writing—Review & Editing. All authors have read and agreed to the published version of the manuscript.

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Not applicable, as the study did not involve human or animal subjects.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author [Changhong Zhan], upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

References

1. 2022 Global Status Report for Buildings and Construction. Available online: https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction (accessed on 1 June 2026).
2. Filippín, C.; Larsen, S.F. Energy efficiency in buildings. In *Energy Efficiency, Recovery and Storage*; Nova Science Publishers: Hauppauge, NY, USA, 2001.
3. Research Center for Building Energy Efficiency, Tsinghua University. *Annual Development and Research Report on Building Energy Efficiency in China 2025 (Urban Residential Housing)*; China Construction Industry Press: Beijing, China, 2025.
4. Bao, M.; Xie, Y.; Zhang, X.; et al. Performance Improvement of a Control Valve with Energy Harvesting. *Energy* **2023**, *263*, 125862. https://doi.org/10.1016/j.energy.2022.125862.
5. Zhao, P.; Yin, J.; Wang, J. Performance Analysis of Control Valves for Supply–Demand Balance Regulation in Heating Stations. *Buildings* **2025**, *15*, 1624. https://doi.org/10.3390/buildings15101624.
6. Si, H.; Ren, Y.; Guo, K.; et al. Flow and Droplet Evaporation Characteristics of High Parameter Temperature and Pressure Reducing Valves under Off-Design Conditions. *Case Stud. Therm. Eng.* **2026**, *80*, 107855. https://doi.org/10.1016/j.csite.2026.107855.
7. Zhang, G.; Qi, S.; Zhu, Z.; et al. Numerical Study on Cavitation Characteristics and Flow Field Instability in a Butterfly Valve under Choked Conditions. *Int. J. Multiph. Flow* **2026**, *198*, 105647. https://doi.org/10.1016/j.ijmultiphaseflow.2026.105647.
8. Trica, D.J. Multi-Loop PID Tuning Strategy Based on Non-Iterative Linear Matrix Inequalities. *Comput. Chem. Eng.* **2025**, *199*, 109137. https://doi.org/10.1016/j.compchemeng.2025.109137.
9. Santos, J.E.W.; Trierweiler, J.O.; Farenzena, M. MIMO PID Tuning for Nonminimum Phase Systems: Setting Attainable Limits for a Stable Behaviour. *IFAC-PapersOnLine* **2019**, *52*, 964–969. https://doi.org/10.1016/j.ifacol.2019.06.187.
10. Sarbu, I.; Valea, E.S. Energy Savings Potential for Pumping Water in District Heating Stations. *Sustainability* **2015**, *7*, 5705–5719. https://doi.org/10.3390/su7055705.
11. Housh, M.; Salomons, E. Energy-Efficient Local Control Strategies for Pumping Stations with Variable-Speed Pumps: A Practical Model-Based Approach. *J. Clean. Prod.* **2025**, *498*, 145131. https://doi.org/10.1016/j.jclepro.2025.145131.
12. Shi, L.; Lao, W.; Wu, F.; et al. DDPG-based load frequency control for power systems with renewable energy by DFIM pumped storage hydro unit. *Renew. Energy* **2023**, *218*, 119274. https://doi.org/10.1016/j.renene.2023.119274.
13. Wang, H.; Wang, S.; Shan K. Experimental study on the dynamics, quality and impacts of using variable-speed pumps in buildings for frequency regulation of smart power grids. *Energy* **2020**, *199*, 117406. https://doi.org/10.1016/j.energy.2020.117406.