Research on Key Technologies and Engineering Application for Energy Saving in Billet Hydraulic Station

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Abstract: As a key power unit for metallurgical equipment, the continuous casting billet hydraulic system often suffers from high energy consumption due to excessive design redundancy and prolonged high-pressure operation. Addressing this issue, this study takes the high-flow 'two-operation, one-standby' billet hydraulic station at Huaisteel as the research subject. A comprehensive energy-saving improvement method was proposed and implemented, integrating system pressure reset based on load matching, action parameter optimization for flow balance, and reconstruction of pump station operation mode utilizing accumulators for peak shaving and valley filling. Firstly, through mechanical analysis and field measurement, the minimum required system pressure was determined based on the billet turning action, lowering the constant pressure set point from 16 MPa to 11 MPa. Secondly, without compromising production rhythm, the action times for the turning, raking, and collection table cylinders were optimized to 25, 15, and 20 seconds respectively, effectively flattening peak flow demand. Finally, by optimizing accumulator pre-charge pressure and pump control logic, the system operation mode was successfully changed from 'two pumps in constant high-pressure mode' to 'single variable displacement pump as main supply with accumulator assistance'. Industrial test results show that after modification, the average operating power of the main motor decreased by approximately 52%, hydraulic oil temperature dropped by 15°C, and the estimated annual electricity saving under equivalent production load reaches 280,000 kWh. This research not only solves the energy consumption problem of the specific equipment but also provides a systematic and quantifiable engineering practice example for the energy-saving design and renovation of similar high-flow intermittent hydraulic systems.

Keywords: Continuous Casting; Hydraulic System; Billet Turner; Billet Raker

1. Introduction

Against the backdrop of the 'Dual Carbon' strategy and manufacturing industry upgrading, energy conservation and consumption reduction in metallurgical processes are crucial for enterprise competitiveness and societal sustainable development [1]. Hydraulic systems, serving as the power core for key processes like continuous casting, account for a significant portion of energy consumption. Hydraulic stations for processes such as billet discharge are often designed for extreme conditions, leading to widespread issues like capacity redundancy and long-term high-pressure relief operation. This results in low energy efficiency and high operational costs [2]. Therefore, implementing cost-effective energy-saving modifications to existing systems holds direct practical significance for reducing costs and enhancing green manufacturing levels [3].

Current research on hydraulic system energy saving predominantly focuses on adopting new hardware like variable frequency drives or optimizing single components such as pump sources. There is a lack of holistic, dynamic co-optimization considering the entire 'system pressure - actuator demand - power response' chain. This often leaves energy-saving potential untapped and can even cause issues like slow response [4]. For the vast number of traditionally deployed valve-controlled and constant pressure variable pump systems, there is an urgent need to explore optimization paths that are low-cost, high-return, and do not compromise stable operation.

To this end, this paper takes the continuous casting billet discharge hydraulic station at Huaisteel as the subject, aiming to systematically address its high energy consumption problem akin to 'using a powerful system for light loads.' Differing from single-component modifications, this study proposes and implements a comprehensive optimization strategy: determining the minimum required system pressure through testing, optimizing the action sequence of each mechanism to smooth flow demand peaks, and reconstituting the cooperative logic between accumulators and pump units. By deeply excavating system potential and achieving refined matching, the goal is to realize significant energy savings without substantial hardware investment

2. Analysis of Current Hydraulic System and Energy Consumption Diagnosis

2.1 System Composition and Process Flow

The billet discharge hydraulic system utilizes three A4VSO180DR/30DR-PBB13N00 axial piston variable displacement pumps (rated displacement 176 L/min), each driven by a 55 kW motor. Under normal operation, it employs a 'two-operation, one-standby' mode. The system is equipped with three sets of accumulators as auxiliary power sources, with the working pressure set within the range of 16-18 MPa. The system's actuators include:

Billet Turner: Five cylinders (125/90-450 mm) responsible for flipping the cast billet from the roller table to the transfer guide.

Billet Raker: Two cylinders (180/100-850 mm) that transfer the billet from the guide to the cooling bed.

Collection Table: Two cylinders (180/100-850 mm) that perform final arrangement of billets on the cooling bed prior to stacking.

The process strictly follows the continuous casting production rhythm: after each billet is flipped, every two billets trigger one raking action. The collection cylinders then perform the final arrangement. The entire hydraulic system must support a maximum continuous production capacity of 40 billets per hour.

2.2 Theoretical Flow Demand Calculation

The actual system flow demand was precisely calculated based on the geometric parameters and operational frequency of each actuator, as presented in Table 1 and Table 2 below.

Table 1: Hydraulic Oil Requirement per Single Action for Each Actuator.

Cylinder	Bore (mm)	Rod Diameter (mm)	Stroke (mm)	Quantity	Action
Lifting	125	90	450	5	Lift/Turn & Lower
Pushing	180	100	850	2	Push Billet &

Collecting	180	100	850	2	Return Push Billet & Return

Table 2: Analysis of Hourly Flow Demand.

Action Type	Action Frequency (times/hour)	Hourly Oil Consumption (L)	Average Flow Demand (L/min)
Turning Action	125	90	450
Pushing Action	180	100	850
Collecting Action	180	100	850
Peak Total Demand	-	4120.6	68.67

Analysis of calculation results: The maximum theoretical flow demand of the system is 68.67 L/min. The rated displacement of a single pump (176 L/min) already reaches 256% of the required flow. In actual operation, two pumps operate in parallel, providing a total supply capacity of 352 L/min, which is 512% of the actual demand, indicating severe configuration redundancy.

2.3 Energy Consumption Problem Diagnosis

Excessively High Pressure Setting: On-site measurement data indicates the system pressure is set at 16-18 MPa. However, based on mechanical analysis of the billet turning process [5], the actual required pressure is only:

$$P_{min} = \frac{F_{load}}{A_{pistom}} + \Delta P_{system}$$

F_{load} is the load equivalent to the maximum billet turning torque, A_{piston} is the effective area of the cylinder, and ΔP_{system} represents the pipeline pressure loss.

Diagnosis reveals four key energy consumption issues in this discharge hydraulic station: The system pressure is set at 16-18 MPa, exceeding the actual requirement of 10-12 MPa by approximately 50%, leading to substantial overflow losses. Severe pump redundancy exists. The dual-pump parallel supply capacity is 512% of the actual peak demand, resulting in an average load rate below 20%. The overlapping action sequences of the actuators cause drastic fluctuations in flow demand. Improper accumulator parameter settings prevent them from fulfilling their 'peak-shaving and valley-filling' function. Theoretical analysis indicates that reducing the pressure to 12 MPa could lower pump power by 33%. Furthermore, switching to single-pump operation with accumulator support could reduce pumping losses by over 50%, demonstrating significant system energy-saving potential.

3.Design of a Comprehensive Energy-Saving Improvement Plan

3.1 Optimization of Process Action Parameters

The core of this solution lies in first conducting in-depth optimization on the 'demand side.' One root cause of the original system's high energy consumption was that the actuator action parameters prioritized 'speed' over 'efficiency,' leading to frequent high instantaneous flow demand peaks. We established a three-pronged optimization strategy: 'reduce frequency, extend duration, lower speed.'

The PLC control logic was optimized by eliminating the no-load stroke of the collection table cylinders, directly reducing ineffective work in the system. While maintaining the unchanged production cycle time (60 seconds/cycle), the action time of the turning cylinders was significantly extended from 5 seconds to 25 seconds. This dramatically lowered their instantaneous flow demand peak and mitigated mechanical shock. By reducing the opening of the flow control valves in each cylinder circuit and optimizing the ramping of the solenoid valve controls, an overall reduction in operating speed and smoother movements were achieved. According to the flow rate formula $Q = A \times v$, decreasing the speed (v) directly and linearly reduces the required instantaneous flow rate (Q). After comprehensive optimization, the system's flow demand curve was effectively 'smoothed,' with the peak demand dropping from over 180 L/min to below 95 L/min. This laid the foundation for simplifying the subsequent power source configuration.

3.2 Reduction of Working Pressure and Optimization of Accumulator Configuration

Building upon the demand-side optimization, the second step involves the precise resetting of the core energy supply parameters. As indicated in the analysis, the original system's working pressure of 16-18 MPa, set based on extremely conservative design principles, far exceeded actual requirements. By establishing a mechanical model of the billet turning process and conducting on-site measurements (manually operating the turner to the critical lifting point of the billet), the minimum necessary pressure to fulfill all process actions was determined to be approximately 11 MPa. Lowering the system's constant pressure set point to this value alone can theoretically reduce the pump's power output by over 30%.

Simultaneously, an efficiency activation retrofit was implemented for the three sets of accumulators that were previously idle in the original system. Firstly, based on the new system working pressure, their nitrogen pre-charge pressure was reset to 9.5 MPa (approximately 85% of the working pressure), placing them within the optimal operational range. Secondly, a pressure operating band of 10.5-11.5 MPa was established in the control logic. When the system pressure exceeds 11.5 MPa, the accumulators store hydraulic fluid. When actuator actions cause the pressure to drop below 10.5 MPa, the accumulators are given priority to release stored fluid for supplementation. This configuration transforms the accumulators from 'static backup vessels' into 'dynamic pressure regulation and stabilization hubs,' effectively absorbing pressure shocks caused by flow fluctuations, greatly stabilizing the system pressure, and creating the conditions for stable single-pump operation.

3.3 Reconstruction of Pump Station Operation Mode

Following the optimization of system demand and supply benchmarks, the final step involved reconstructing the operation mode of the hydraulic power source. Calculations confirmed that the optimized system's maximum instantaneous flow demand (<95 L/min) is far lower than the rated displacement of a single variable pump (176 L/min) [6]. The original redundant design of 'two-operation, one-standby' was deemed unnecessary, and conditions were met to switch to single-pump operation.

The switch adhered to the principle of 'minimum modification, maximum safety.' In terms of hardware, only the outlet isolation valves of Pump 2 and Pump 3 were closed. At the control level, the PLC program was modified to cancel the dual-pump operation, retaining only Pump 1 as the main pump performing automatic variable displacement regulation based on pressure. Pump 2 was set to manual mode for emergency use, and Pump 3 remained in cold standby, thereby maintaining the original triple redundancy reliability of the system. This new mode can be summarized as 'single variable displacement pump for constant pressure supply as the primary source, with accumulators providing dynamic compensation as the auxiliary.' This allows the single pump to operate within its high-efficiency load range, avoiding efficiency losses associated with parallel operation and frequent relief valve operation. The accumulators level out periodic flow fluctuations, fundamentally resolving the long-standing contradiction of chronic oversupply capacity. This shift transforms energy utilization from 'continuous waste' to 'on-demand supply,' achieving a significant leap in energy efficiency.

4.Engineering Implementation and Effect Verification

4.1 Implementation Steps and Key Technical Points

To ensure a safe and orderly retrofit, the project followed a rigorous sequence of steps. First, system safety isolation was performed, including planned shutdown, pipeline pressure relief, and Lockout-Tagout (LOTO) of electrical cabinets, creating safe working conditions.

The control program in the PLC was modified to eliminate the no-load cycle of the collection table cylinders. The action times for the turning, raking, and collection table cylinders were set to 25, 15, and 20 seconds respectively, with optimized start-stop curves implemented for soft starts and stops. The openings of the throttle valves were adjusted on-site to reduce steady-state speeds by 20%-30%.

The pressure set point of the variable pump was lowered from 16-18 MPa to 11 MPa. The accumulator pre-charge pressure was set to 9.5 MPa, with the operating pressure range defined as 10.5-11.5 MPa.

The outlet isolation valves for Pump 2 and Pump 3 were closed to isolate them from the main line. The PLC program was modified to disable dual-pump, leaving only Pump 1 to regulate automatically based on pressure. Pump 2 was set for remote manual operation in emergencies, and Pump 3 was kept in cold standby. Additional low-pressure alarm interlock logic was added.

4.2 Experimental Verification Plan

To objectively evaluate the retrofit effects, a 72-hour continuous test under normal production conditions (casting speed of 1.2 m/min, 40 billets/hour) was conducted during the first week after the modification. High-precision monitoring was performed synchronously using an electrical power analyzer, pressure sensors, and temperature sensors to measure main motor power, system pressure, and oil temperature. Action times and production rhythms were recorded via the PLC and stopwatch. All data was collected at a frequency of 1 Hz and fed into the SCADA system to generate trend curves and reports, ensuring data integrity and reliability.

4.3 Comparative Analysis of Operational Data Before and After Retrofit

Comparing the post-retrofit data with the historical operational records of the original system revealed extremely significant energy-saving effects and system state improvements, the core data comparison is presented in Table 3 below.

In terms of power consumption, after switching from dual-pump to single-pump operation, the average input power of the main motor decreased from approximately 78 kW to 43 kW, a reduction of 44.9%. Based on an annual operation of 8000 hours and an electricity price of 0.8 RMB/kWh, the estimated annual electricity saving is about 280,000 kWh, translating to a cost saving of approximately 224,000 RMB.

As shown in Table 3, the system's operational status was comprehensively optimized. The working pressure stabilized within the optimized range of 10.5-11.5 MPa. The relief valve transitioned from frequent opening to being essentially closed, fundamentally curbing energy waste. The average hydraulic oil temperature decreased significantly from 58-62°C to 42-45°C, a drop exceeding 15°C, which greatly slows down oil oxidation and seal aging. Equipment operating noise was reduced from approximately 86 dB(A) to around 76 dB(A), markedly improving the working environment. In terms of production efficiency, the single-cycle production time slightly increased from 60 seconds to 62 seconds. Confirmation with the production department indicated this change falls within the permissible process margin and has no impact on overall capacity. Throughout the testing period, system pressure remained stable, all actuators operated smoothly and accurately, and the standby pump was never triggered to start, demonstrating the reliability and stability of the single-pump operation mode.

Table 3: Optimization of System Operating Status.

Monitoring Item	Before Modification (Dual Pump Operation)	After Modification (Single Pump Operation)	Change / Status
Number of Running Pumps	2	1unit	Reduced by one unit
Motor Average Input Power	78KW	43KW	Decreased by 44.9%
System Working Pressure	16-18Mpa	10.5-11.5Mpa	Decreased by ~31%, more stable
Hydraulic Oil Temperature (Stable)	58-62℃	42-45℃	Decreased by15-20C
System Noise	86dB (A)	76dB (A)	Decreased by 10 dB(A)
Single Cycle Production Time	60 seconds	62 seconds	Increased by 2 seconds
Relief Valve Operating Status	Frequent opening, heating	Mostly closed	Significantly improved

5.Discussion and Analysis

The significant energy saving achieved in this retrofit (a 44.9% reduction in motor power) stems from the synergistic effect of four key technologies: pressure reduction, single-pump operation, motion optimization, and accumulator activation. Lowering the system working pressure from 16-18 MPa to 11 MPa directly reduced the pump's output power. Switching the operation mode from dual-pump to a single variable displacement pump serving as the primary supply avoided losses associated with parallel operation. By extending action times and reducing speeds, the peak flow demand was cut from over 180 L/min to below 95 L/min, allowing the pump to operate continuously within its high-efficiency zone. The reconfiguration of the accumulators stabilized pressure fluctuations. The retrofit also delivered comprehensive benefits including a 15-20°C reduction in oil temperature, an approximate 10 dB(A) decrease in noise, and extended lifespan for key components, substantially improving system energy efficiency and operational economy.

The core advantage lies in replacing expensive hardware upgrades with ‘refined software and parameter optimization.’ Energy savings were primarily achieved by adjusting control logic and system parameters, with minimal hardware modifications. Consequently, this approach features an extremely short payback period, low implementation risk, and non-destructive integration with the existing structure, providing a cost-effective 'potential-tapping and efficiency-enhancing' pathway for existing hydraulic systems.

As indicated in the analysis, the successful application of this solution relies on three prerequisites: first, the original system must exhibit significant 'overcapacity' akin to 'using a big horse for a small cart'; second, the production process must allow adjustments to actuator speed and timing; third, key hydraulic components must be in good condition to adapt to the new operating parameters.

The limitations of the solution are that it is primarily suitable for periodic, intermittent medium-to-high pressure systems with low requirements for dynamic response and synchronization precision. Its energy-saving potential is constrained by the original system's redundancy level. Once optimal matching is achieved, further energy savings would require advanced technologies such as variable frequency drives.

The methodological framework of →diagnosing redundancy → optimizing demand → resetting benchmarks → reconstructing supply' proposed in this study provides an efficient and low-cost promotion pathway for energy-saving retrofits of intermittent, high-load hydraulic systems like continuous casting billet discharge. It also encourages moving away from rough component sizing in new system designs, instead employing refined analysis to avoid 'over-design' from the outset. Looking forward, technologies such as variable frequency drives, IoT monitoring, and adaptive control can be integrated on this foundation to achieve dynamic optimization of energy-saving benefits and intelligent operation and maintenance, propelling industrial hydraulic systems toward greater efficiency, sustainability, and intelligence.

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