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# Online hydraulic calculation and operation optimization of industrial steam heating networks considering heat dissipation in pipes

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ABSTRACT

Constructing industrial parks with DH (district heating) systems has become a main way to develop modern industry, which requires strict security and reliability of heating networks. Industrial steam heating networks are usually ring-shaped with multiple heating sources, and the working conditions would be changeable due to the high frequency and a wide range of load variation of heating consumers. Under a specific working condition, low steam velocity for a long time (namely “steam stagnation”) in certain pipes will result in CIWH (condensation-induced water hammer) which will threaten the security of the whole DH system. In this paper, a hydraulic calculation model is built to study the steam flow regime considering heat dissipation and condensation in pipes, an operation optimization method is proposed to help eliminate steam stagnation through optimizing the heat load distribution of each heating source, a general software system entitled “HEATNET” is presented to realize online hydraulic calculation and operation optimization for arbitrary structured heating networks. The practical application of HEATNET in Shanghai chemical industry zone shows that heat dissipation and condensation in pipes would influence the overall hydraulic calculation of steam heating networks and it can prevent CIWH and improve the security and reliability of steam heating networks.



## 1. Introduction

In recent years, constructing centralized industrial parks with DH (district heating) systems for specific industries has become an important development pattern in China [1]. Replacing self-built boiler rooms with DH systems in industrial parks is of great significance in improving the reliability and economy of heating systems [2,3].

What's more, a substantial reduction in fuel demands and $CO_2$ emissions as well as cost can be achieved, and it is also easy for pollutants centralized processing by converting to district heating [4,5]. As a successful model, by means of energy conservation and expansion of CHP (Combined Heat and Power production), Denmark has been able to maintain the same primary fuel consumption for a period of more than 30 years in spit e of about 70% increase in GDP (Gross Domestic Product) [6].

A DH system mainly includes three parts: heating sources, heating consumers and heating pipe system [7]. Heating pipe system, which transports heat generated in heating sources to heating consumers is the most complicated part of a DH system.

Compared with civil DH systems, industrial DH systems have several special characteristics: as the steam affects the manufacturing process and the production security of heating consumers, the heating pipe system needs to be more secure and reliable; ring-shaped heating networks with multiple heating sources are commonly used in industrial DH systems to improve the stability of heat supply; there might be heat-return steam consumers, which produce steam and supply them to heating networks in some working conditions; the high frequency and a wide range of load variation of industrial heating consumers may lead to complicated steam flow regime, hydraulic maladjustment or even steam stagnation in certain pipes, and steam stagnation

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**Nomenclature**

| | |
|---|---|
| **V** | set of nodes |
| **E** | set of sections |
| **C** | set of fundamental circuits |
| $M$ | the number of sections |
| $N$ | the number of nodes |
| $S$ | the number of fundamental circuits |
| $A$ | matrix connecting nodes and sections |
| $B$ | matrix connecting sections and circuits |
| $\boldsymbol{q}$ | column vector of mass flow rate of nodes |
| $\boldsymbol{Q}$ | row vector of mass flow rate of sections |
| $q$ | node mass flow rate (kg/s) |
| $Q$ | section mass flow rate (kg/s) |
| $\boldsymbol{\Delta P}$ | row vector of pressure drop in each section |
| $\Delta P_{flow.m}$ | flow resistance pressure drop in $E_m$ (Pa) |
| $\Delta P_{gra.m}$ | gravitational pressure drop in $E_m$ (Pa) |
| $\Delta P_{dyn.m}$ | dynamic pressure drop in $E_m$ (Pa) |
| $\Delta P_{friction.m}$ | friction resistance in $E_m$ (Pa) |
| $\Delta P_{local.m}$ | local resistance in $E_m$ (Pa) |
| $\xi$ | total local resistance coefficient |
| $\lambda'$ | friction resistance coefficient |
| $l$ | length (m) |
| $\rho$ | density (kg/m$^3$) |
| $w$ | velocity (m/s) |
| $D$ | diameter (m) |
| $\kappa$ | Roughness |
| $Re$ | Reynolds number |
| $Pr$ | Prandtl number |
| $Nu$ | Nusselt number |
| $\Phi$ | heat transfer rate (W/m) |
| $K$ | heat transfer coefficient (W/m$^2$ K) |
| $\delta$ | thickness (m) |
| $h$ | convection heat transfer coefficient (W/m$^2$ K) |
| $\lambda$ | conductivity coefficient (W/m K) |
| $T$ | temperature (K) |
| $t$ | temperature (°C) |
| $P$ | pressure (MPa) |
| $\varepsilon$ | emissivity |
| $\sigma$ | Stefan–Boltzmann constant (W/m$^2$ K$^4$) |
| $\upsilon$ | kinematic viscosity (m$^2$/s) |
| $N_{st}$ | number of steam traps |
| $N_{hc}$ | number of heating consumers |
| $N_{hs}$ | number of heating sources |
| $I$ | enthalpy (kJ/kg) |
| $\Delta Q$ | regulated flow rate (kg/s) |
| $\Delta H$ | loop closure (Pa) |
| $F$ | area (m$^2$) |
| $\varepsilon_{tot}$ | given precision of overall calculation |
| $\varepsilon_{st}$ | given precision of drainage calculation |
| $\sum q_{nst}$ | theoretical total drainage of steam traps |
| $N_{hc.re}$ | number of heat-return consumers |
| $N_{hc.use}$ | number of heating consumers which use steam |

*Subscripts and abbreviations*

| | |
|---|---|
| DH | district heating |
| CIWH | condensation-induced water hammer |
| $n$ | serial number of a node |
| $m$ | serial number of a section |
| $s$ | serial number of a fundamental circuit |
| $p$ | pipe |
| $isu$ | insulation |
| $a$ | air |
| $r$ | radiation |
| $m.c$ | condensation layer in $E_m$ |
| $m.ms$ | main steam in $E_m$ |
| $sh$ | superheated steam |
| $w$ | saturated water |
| $nst$ | serial number of a steam trap |
| $nhc$ | serial number of a heating consumer |
| $nhs$ | serial number of a heating source |
| $i$ | iteration number of flow regulation |
| $j$ | iteration number of overall calculation |

would result in some serious accidents, such as CIWH (condensation-induced water hammer).

For industrial DH systems, operators can hardly get the real-time steam flow regime in each pipe for the lack of related measuring devices to record the flow rate, temperature and pressure of steam. However, with the rapid development of computer technology, the combination of the heating network hydraulic calculation model, real-time steam parameters of heating sources and consumers makes it possible to calculate the steam flow regime theoretically online and realize operation optimization for heating networks. In the online hydraulic calculations, more attention should be paid to the drainage of all steam traps, which is induced by heat dissipation in pipes since it can reach 3–10% of the total heat supply.

At present, when calculating the steam flow regime in the pipes of a ring-shaped network, graph theory [8–12] and Kirchhoff's law [9,13] are used to divide the network into several loops and to analyze the hydraulic condition with numerical methods [14] respectively. Technical University of Denmark [15] and software TERMIS [16] put forward a "node method" to simulate the temperature dynamics of DH systems, Irina Gabrielaitiene et al. [17] validated this method with time dependent consumer data from a Naestved DH system. Stevanovicet et al. [18] presented a method for numerical simulation and analysis of the steady state hydraulics of complex pipeline networks, which was based on the loop model of the network and the square roots method for solving the system of linear equations. In terms of business software, FLOWRA32 can simulate real-time data in heat exchange stations online and analyze the energy consumption, TERMIS [16] can optimize the operation of DH systems according to different working conditions and ambient conditions. They both can guide the design and operation of DH systems, save energy and reduce cost for heat-supply companies.

For the water hammer phenomenon in steam heating networks, M. H. Chaudhryet et al. [19] had described the features of water hammer early in 1987. As one of the main reasons that leads to water hammer [20], CIWH is an undesirable side effect which would result in instability [21] and hydraulic shock [22,23], and CIWH may cause a serious damage to equipment and endanger lives of working staff [24]. Much of previous research on CIWH was based on RELAP5, but M. Valinciuset et al. [25] and W. Zhou et al. [26] both identified the limitations of RELAP5 in their research projects. Based on the study of R.W. Bjorge and P. Griffith [27], M. H. Chunet et al. [22] presented a computer code entitled "KAIST-CIWH" and the sample guide charts to find CIWH free regions for a given combination of major flow parameters in a long horizontal