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Research Paper

Determining optimum insulation thickness by thermoeconomic analysis for a pipeline system in a subway central cooling system

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HIGHLIGHTS

- Determine OIT of a pipeline system using thermoeconomic analysis.
- OIT is higher for exergoeconomic optimization than for energoeconomic optimization.
- The cooling loss and the OITs significantly differ between the FCW and UCW.
- EC method is a good way for economic impacts considered.
- EPC method is a better choice for environmental advantages considered.

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ABSTRACT

Thermoeconomic analysis combines exergy and economic analysis to evaluate and improve the performance of energy systems. This study utilized exergetic production cost (EPC), based on combined exergy and life-cycle cost analysis (LCCA), to optimize the insulation thickness of a pipeline system with a variable secondary pump in a subway central cooling system. The effects of the selected variables on insulation thickness optimization were also investigated. The results of the EPC and energetic cost (EC) methods were compared using payback period and total environmental impact of the pipe system, respectively. Results showed that the optimum insulation thickness (OIT) is higher for exergoeconomic optimization than for energoeconomic optimization. EC method is a good way for economic impacts considered, while EPC method is a better choice for environmental advantages considered. Moreover, cooling loss and the OIT significantly differ between fresh and used chilled water. Therefore, the characteristics of the supply and return pipes should be jointly considered in calculating the insulation thickness.

1. Introduction

Subway systems provide economic and convenient public transportation means within cities. As an important public infrastructure, subway stations are constantly located in densely populated areas. As such, problems relating to the relentless noise and heat emission of air conditioners have arisen because of the poor layout of the chiller plants and cooling towers for subway station refrigeration. Thus, centralized cooling schemes for underground stations have drawn considerable attention [1].

A subway central cooling system centralizes chiller plants and cooling towers from different neighboring subway stations to one place and then transports chilled water to the air terminal devices of different stations through pipeline systems. Compared with individual cooling systems, central cooling systems present advantages in environmental protection, landscape, and operation management because they do not require large chillers and cooling towers outside the stations. However, they are also limited by their high convective heat transfer coefficient due to the high-temperature and high-velocity piston wind in subway tunnels, and the high cost of investment and maintenance for the insulation pipelines and variable secondary water pumps due to long-distance transportation (radius = 1500–3000 m).

Effective thermal insulation of piping systems can reduce the heat loss and energy consumption for the heat transmission and distribution

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Nomenclature

q	heat flux of the unit pipe length (W)
L	transportation radius (m)
T_w	average temperature of the FCW or UCW (°C)
T_{air}	average air temperature in the tunnel (°C)
K	overall coefficient of heat transfer (W/[m^2 °C])
λ_{steel}, λ_{insu}	heat conductivity coefficients of the steel pipe and thermal insulation material, respectively (W/[m K])
d_{in}, d_{steel}	internal and external diameters of the steel pipe, respectively (m)
d_{out}	external diameter of the insulated pipe (m)
θ_{steel}	thickness of the steel pipe (m)
θ_{insu}	thickness of the insulation material (m)
θ_{anti}	anti-condensation thickness (m)
α_{in}, α_{out}	internal and external convective heat transfer coefficients, respectively (W/[m^2 K])
λ_w	heat conductivity coefficient of water (W/[m K])
μ_w	viscosity of water (Pa s)
cp_w	specific heat of water (J/[kg °C])
ρ_w, ρ_{insu}	density of water and insulation material (kg/m^3), respectively
u_w	flow rate of chilled water (m/s).
u_{air}	air flow rate in tunnel (m/s)
ε	emissivity of the external surface of the insulated pipe
T_{out}	external surface temperature of the insulated pipe (°C)
W_{pum}	power consumption of the variable secondary pump (kW)
η	pump efficiency
G	volume flow of the chilled water (m^3/s)
Δp	total resistance loss of the pipelines (Pa)
δ	coefficient of local resistance of the piping system
γ	on-way resistance coefficient
K_s	equivalent roughness of the steel pipe (m)
Z_{pum}	investment cost of the variable secondary pump ($)
Z_{pipe}	investment cost of pipeline ($)
Z_L	equivalent annual repay cost ($/h)
Ψ	system maintenance factor
H	annual running hours of the system (h/yr)
ζ	repay factor (1/h)
P	annual factor
n	lifetime of the equipment (year)
r	parameter depending on inflation and interest rates
g	inflation rate (%)
i	interest rate (%)
y	unit EC ($/kW)
Q_{load}	cooling load at the station (kW)
$Y_{\Delta Q}$	cost resulted from the cooling loss ($/h)
Y_{pum}	cost of the energy consumed by the pump ($/h)
$Z_{\Delta Q}$	additional capital investment of the chiller station ($/h)
c_e	electricity price ($/kWh)
COP	COP of the chiller plants
F_s	initial investment of the chiller station per unit cool energy ($/kW)
c_2	unit EPC of output exergy ($/kW)
Ex_1	input exergy of pipeline system (kW)
Ex_2	output exergy of pipeline system (kW)
c_1	unit EPC of input exergy ($/kW)
$Ex_{FCW,in}$	input exergy of FCW (kW)
$Ex_{FCW,out}$	output exergy of FCW (kW)
$Ex_{UCW,in}$	input exergy of UCW (kW)
$Ex_{UCW,out}$	output exergy of UCW (kW)
P_b	payback period (year)
As	annual energy saving ($/yr)
Z_{insu}	investment cost of insulation materials ($)
B	total environmental impacts (mPts/h)
b_e	environmental impact point (mPts/kWh)
b_{coal}	environmental impact point (mPts/MJ)
b_{insu}	environmental impact point (mPts/kg)
m_e	electricity consumption due to cooling loss (kWh)

in district heating/cooling. An increase in insulation thickness decreases the energy consumption for heating/cooling, but increases the investment cost [2]. Thus, the optimum point must be determined, at which both the total investment cost and energy consumption can be minimized over the system's lifetime [3,4]. Moreover, a decrease in pipe diameter reduces the investment cost for chilled water transportation, but increases the energy consumption of variable secondary water pumps; thus, an optimum pipe diameter and flow rate must be determined. Selecting the appropriate insulation material and obtaining the optimum values for pipe diameter, insulation thickness, and flow rate are critical.

Considering the great potential for energy savings, previous studies have mainly focused on the optimal insulation thickness (OIT) for buildings [5–9], refrigeration applications [10], stores [11,12], district heating [2,13,14], and so on. The OIT for exterior walls in different regions was calculated and a proposal of OIT for the exterior walls of buildings in 32 regions of China was put forward to save energy and reduce CO_2 emissions [7]. The optimal thermal resistance (OTR) of insulation materials, energy cost saving per unit area of external walls and payback periods were estimated via a cost analysis and degree-day (DD) method [8]. A numerical model was used to determine the annual thermal transmission loads, then the calculated thermal transmission loads were inputted to an economic model to determine the OIT for a south-facing wall in the climatic conditions of Elazığ, Turkey [9]. The OIT of pipes was determined depending on life-cycle cost analysis (LCCA), and the economic and environmental impacts of insulation in district heating pipelines were discussed [2,13]. The OIT in pipes was analysed based on two different methods (life cycle assessment and life cycle cost) used to determine the OIT for environmental impact reduction of pipe insulation [14]. However, most of these studies, have based optimization on energetic cost (EC) or environmental impacts. Exergy analysis is effective for assessing the performance of thermal systems. It provides a more comprehensive information than energy analysis [15]. Thermoeconomic analysis combines exergy and economic analysis to evaluate and improve the performance of energy systems [16]. It provides an assessment procedure for the unit cost of the products of a system to achieve a cost-effective design and operation [17].

Few studies [3,18], have presented thermoeconomic techniques for the optimum design of hot water piping systems. In the present study, an exergetic production cost (EPC) was utilized to optimize the insulation thickness of the pipeline system that transports chilled water from chiller plants to underground railway stations. The EPC is based on combined exergy and LCCA. The EPC and EC equations were formulated as a function of the operating parameters and they were solved by use of Linear Interactive and General Optimizer (LINGO 11.0) [19] to minimize unit EPC and unit EC. The effects of the selected variables on insulation thickness optimization were investigated. Moreover, a comparison between the results of EPC and EC methods was performed by using payback period and total environmental impact of the pipe system, respectively. Thus, the method which are better for application was determined.