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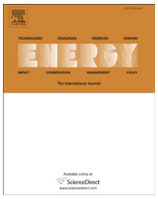

Determination of the economical optimum insulation thickness for VRF (variable refrigerant flow) systems

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ABSTRACT

This study deals with the investigation into optimum insulation thickness of installed inside building pipe network of VRF (variable refrigerant flow) systems. Optimum insulation thickness, energy savings over a lifetime of 10 years and payback periods are determined for high pressure gas pipelines, low pressure gas pipelines and low pressure liquid pipelines under the heating-only and cooling-only modes of the three-pipe VRF system using R-410A as refrigerant. By using the P_1-P_2 method, the value of the amount of the net energy savings is calculated. Under heating mode of VRF system, while the optimum insulation thickness varies between 16 and 20 mm depending on the pipe sections of high pressure gas pipeline, it varies from 11 to 13 mm for the pipe sections of low pressure liquid pipeline. Under cooling mode of VRF system, the optimum insulation thickness varies between 7 and 8 mm for pipe sections of low pressure gas pipeline and low pressure liquid pipeline.

1. Introduction

VRF (variable refrigerant flow) systems use one external unit that is connected to several indoor units. VRF systems are popular because they require less outdoor plant space than conventional central air conditioning systems, are less disruptive in fitting to existing buildings (particularly when occupied), and are able to cool and heat through common pipework. These systems all use refrigerant as the cooling/heating medium rather than chilled water/hot water, which is used in conventional hydraulic systems circulated by pumps [1].

It is estimated that air conditioning systems consume about 50% of the total electricity use in the office buildings. Therefore, reducing energy use for space cooling and heating in buildings is a key measure for the energy-savings [2]. There are many strategies to reduce energy consumption, especially in heating and cooling devices. Using proper insulation in pipe network is perhaps the most effective way of energy conservation for the heating and cooling applications of VRF systems. To minimize the energy and insulation costs in addition to reducing the heat loss to the surroundings, the thickness of the insulation material needs to be optimized. The economic insulation thickness for a pipe is a function of a large number of parameters, such as pipe size, cost, conductivities of the pipe and the insulation material, operating and ambient temperatures, heat transfer coefficients at the inside and outside of the pipe, economic parameters and annual operation The concept of economic thermal insulation thickness considers the initial cost of the insulation system plus the ongoing value of energy savings over the expected service lifetime of the insulation [3].

Determining both the type of thermal insulation material and the economic thickness of the material used in the hot water or air service pipelines are the main subjects of many engineering investigations. Most studies estimated the heating energy requirement by the degree-time concept (degree-day, DD, or degree-hour, DH), which is one of the simplest methods applied under static conditions. Zaki and Al-Turki studied economic analysis of thermal insulation for a system of pipelines, from the oil industry, insulated by different materials composite layers. The analysis was based on an explicit nonlinear cost function that includes the annual energy losses and the insulation initial costs. In the analysis, rockwool and calcium silicate as insulation materials and a system of pipelines (0.1–0.273 m nominal size) with flow of superheated steam, furfural, crude oil, and 300-distillate was employed and h_o was assumed constant, 10 W $m^{-2}K^{-1}$ [4]. Li and Chow analyzed methods for protecting water pipes, in cold regions against freezing, by thermal insulation material and heating cable. They

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Nomenclature

a	high pressure gas pipeline
A	area (m^2)
b	high pressure gas pipeline
c	low pressure liquid pipeline
C	price (\$ kg^{-1}, \$ m^{-3})
COP	coefficient of performance
d	inflation rate (%)
D	diameter (mm)
$\dot{E}$	energy rate (J m^{-1} year^{-1})
ES	energy saving (\$ m^{-1})
h	convection transfer coefficient (W m^{-2} K^{-1})
HDD	heating degree-days (°C-days)
H_u	lower heating value of the fuel (J kg^{-1}, J m^{-3})
i	interest rate (%)
k	the heat transfer coefficient (Wm^{-1} K^{-1})
LCCA	life cycle cost analysis
L	length (m)
m	fuel consumption (kg m^{-1} year^{-1}), (m^3 m^{-1} year^{-1})
N	lifetime (years)
Pr	Prandtl number (–)
PP	payback period (years)
$\dot{Q}$	heat transfer rate (kW, J m^{-1} year^{-1})
R	thermal resistance (KW^{-1})
Re	Reynolds number (–)
t	wall thickness (mm)
T	temperature (K)
U	overall heat transfer coefficient (W m^{-1} K^{-1})
V	velocity (m s^{-1}), volume (m^3)
x	optimum insulation thickness (cm)
η	efficiency
ρ	density (kg m^{-3})
Δt	annual operation time

Subscripts

a	ambient
an	annual
cl	cooling load
cond	condenser
evap	evaporator
f	total fuel
fg	fiberglass
F	fuel
hl	heating load
i	inside
in	inlet
ins	insulation
m	mean
o	outside
opt	optimum
out	outlet
R	refrigerant
s	surface of pipe
t	total
un-ins	un-insulation
1, 2, …5,	branch pipe
6, 7, 8, 9	main pipe

applied a thermoeconomic optimization analysis with a simple algebraic formula derived for estimating the optimum insulation thickness for tubes of different diameters varying from 0.02 m to 0.2 m. They investigated the effects of outdoor air conditions and design parameters on the optimum thickness. For the same outside-air temperature, the optimum insulation-thickness would become larger for lower design insulation envelope outside-temperature. It was also found that the optimum insulation thickness was inversely proportional to the thermal conductivity and cost of the insulating material [5]. Ozturk et al. presented four different thermo-economic techniques for optimum design of hot water piping systems. They were as follows: the first one was a sequential optimization of pipe diameter based on minimization of total cost without considering heat losses and then of insulation thickness based on minimization of cost of insulation and heat losses. The second was simultaneous optimization of pipe diameter and insulation thickness based on the first law of thermodynamics and cost. The third was simultaneous determination of pipe diameter and insulation thickness based on maximization of exergy efficiency without considering cost. Finally, the fourth was simultaneous determination of pipe diameter and insulation thickness based on maximization of exergy efficiency and cost minimization. A case study was carried out for a hot water pipe segment, and the differences and merits of each method were discussed. Important parameters such as annual operation time, depreciation period, interest rate, fuel and electricity prices, and the thermo–physical parameters were assumed to be the same and constant for all methods [6]. Soponpongpipat et al. conducted the optimum thickness analysis of air conditioning duct's insulation, which composes of the layer of rubber and fiber glass insulator, by means of thermo-economics method. The effects of heat transfer coefficient at inside and outside of duct on the optimum thickness of these insulators were studied. The galvanized steel duct diameter of 0.5 m with rubber insulator ($k = 0.035$ W m^{-1}K^{-1}) and fiberglass insulator ($k = 0.045$ W m^{-1}K^{-1}) was selected to show the study results. In order to study the change in optimum thickness when convective heat transfer coefficients were varied, the inside and outside duct convective heat transfer coefficient of 6, 10, 14, 18 and 22 W m^{-2}K^{-1} were selected for calculation of optimum thickness. They demonstrated that the variation of inside and outside duct convective heat transfer coefficient does not affect optimum thickness but net saving increases when inside and outside duct convective heat transfer coefficient increases [7]. Keçebaş et al. calculated the optimum insulation thickness of pipes used in district heating pipeline networks, energy savings over a lifetime of 10 years, and payback periods for the five different pipe sizes and four different fuel types in the city of Afyonkarahisar/Turkey. Rockwool as insulation material and a system of pipelines (50–200 mm nominal sizes) with flow of hot water were considered. The results showed that optimum insulation thicknesses varied between 0.085 and 0.228 m, energy savings varied between 10.041 \$/m and 175.171 \$ m^{-1}, and payback periods varied between 0.442 and 0.808 years depending on the nominal pipe sizes and the fuel types. The highest value of energy savings was reached in 250 mm nominal pipe size for fuel-oil fuel type, while the lowest value is obtained in 50 mm for geothermal energy. Considering the economic and environmental advantages, the geothermal energy was a better choice and then natural gas [8]. Başoğul and Keçebaş investigated the energy, economic and environmental evaluations of thermal insulation in district heating pipeline. The optimum insulation thickness, energy saving over a lifetime of 10 years, payback period and emissions of CO, CO_2 and SO_2 are calculated for