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Effectiveness of a thermal labyrinth ventilation system using geothermal energy: A case study of an educational facility in South Korea

Seung-Yeong Song *, Jin-Hee Song, Jae-Han Lim

Department of Architectural Engineering, Ewha Womans University, 52 Ewhayeodae-gil, Seodaemun-gu, Seoul 120-750, South Korea

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ABSTRACT

Ventilation is essential to maintaining a healthy indoor environment. However, during the summer and winter seasons, the temperature of the outdoor air can be so extreme that providing adequate ventilation requires a significant amount of energy. Consequently, an energy-efficient ventilation system is important for minimizing energy consumption. The thermal labyrinth is a ventilation system that pulls in outdoor air through an underground labyrinth-shaped concrete structure that is part of the building itself. Through heat exchange with the ground, this system can pre-cool and pre-heat the outdoor air in the summer and winter seasons, respectively. The goal of this study was to evaluate the energy performance of the thermal labyrinth ventilation system (TLVS) used in the Ewha Campus Center building recently built in Seoul, South Korea. By using the TLVS, the peak loads for the cooling and dehumidification and the heating and humidification of the outdoor air were found to be reduced by 47.6% and 41.2%, respectively. The annual energy need for conditioning outdoor air was reduced by 31.3%, and a payback period of 12.1 years was calculated.

Introduction

Background and research goals

To maintain healthy indoor air quality, it is essential to disperse and exhaust indoor pollutants by exchanging indoor air with fresh outdoor air through ventilation. The importance of indoor air quality has drawn increasing attention because of the growing amount of time spent indoors by the population and the air-tightness of building envelopes. Indoor air pollution problems result from a lack of ventilation. Therefore, many countries are moving toward strengthening ventilation regulations by setting a mandatory ventilation standard to ensure sufficient ventilation.

In the summer and winter seasons, when the thermal conditions of the outdoor air are poor, the intake of outdoor air for ventilation increases energy consumption. According to Kwon (2010), the outdoor air conditioning loads of business facilities with mechanical ventilation systems account for significant thermal loads (approximately 35% and 40% of building peak cooling and heating loads, respectively). Therefore, it is necessary to use energy-efficient ventilation systems to reduce the energy consumption of buildings.

The goal of this study was to evaluate the energy performance of a thermal labyrinth ventilation system (TLVS), which pre-cools or pre-heats ventilating outdoor air using underground labyrinth-shaped concrete structures of the building itself as intake channels; this system has been implemented in the Ewha Campus Center building in Seoul, South Korea. To investigate the effectiveness of the TLVS, this study analyzed the surface temperature variation of the underground structures, the hygrothermal conditioning effect on the outdoor air, the reductions in the peak load and the annual energy need for conditioning outdoor air to maintain the indoor set-point temperature and humidity conditions, and the increased fan energy use for the intake of outdoor air. By performing an economic feasibility analysis, this study assessed the value of the TLVS.

Research methods

This study investigated examples of the TLVS and reviewed the existing relevant research. After analyzing the construction drawings and the actual site of the Ewha Campus Center building, we measured the surface temperature of the underground walls inside the system, the temperature and humidity of the outdoor air above the ground (OA) and of the outdoor air passing through the TLVS (OATL), and the OATL flow rates for a year. Then, we analyzed the cooling, heating, dehumidification, and humidification effects of the TLVS on the OA by comparing the temperature and the absolute humidity between the OA and the OATL emerging from the TLVS and entering the air handling unit. The reductions in the peak load and the annual energy need for conditioning OA and the increased fan energy use for the intake of OA before and after the application of the TLVS were estimated, and the energy performance was analyzed. The economic feasibility was evaluated by estimating the increase in construction costs and the reduction

* Corresponding author. Tel.: +82 2 3277 3913.
E-mail addresses: archssy@ewha.ac.kr (S.-Y. Song), cco79@naver.com (J.-H. Song), limit0@ewha.ac.kr (J.-H. Lim).

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Nomenclature

TLVS	thermal labyrinth ventilation system
OA	outdoor air above the ground
OATL	outdoor air passing through the TLVS
$q_{coolheat\_TL}$	cooling or heating powers of the TLVS on OA (W, −: cooling, +: heating)
$q_{dehumidhumid\_TL}$	dehumidification or humidification powers of the TLVS on OA (W, −: dehumidification,+: humidification)
Q_{v_OATL}	flow rate of OATL emerging from the TLVS and entering the air handling units (L/s)
T_{OATL_B6}	temperature of OATL in the 6th basement (°C)
T_{OA}	temperature of OA (°C)
W_{OATL_B6}	absolute humidity of OATL in the 6th basement (kg_w/kg_{da})
W_{OA}	absolute humidity of OA (kg_w/kg_{da})
q_s	sensible heat load for conditioning OA (W, −: cooling, +: heating)
q_l	latent heat load for conditioning OA (W, −: dehumidification, +: humidification)
T_i	indoor set-point temperature (°C)
W_i	indoor set-point absolute humidity (kg_w/kg_{da})
Q_s	energy need for conditioning OA due to the sensible heat load (J, −: cooling, +: heating)
Q_l	energy need for conditioning OA due to the latent heat load (J, −: dehumidification, +: humidification)
Δt	measurement interval (900 s)
ΔP_{fan}	difference in the fan electrical power between cases 1 and 2 (kW)
P_{fan}	fan electrical power (kW)
Q_v	air flow rate through the fan (m^3/s)
Δp_{fan}	total pressure rise from fan inlet to outlet (Pa)
η_e	overall efficiency of the fan and motor system
Δp_{TLduct}	total pressure loss in the OA intake duct of the TLVS (Pa)
f	friction factor
L	duct length (m)
D_h	hydraulic diameter (mm)
C	local loss coefficient
ρ	density (kg/m^3)
V	velocity (m/s)
Re	Reynolds number
ε	absolute roughness factor (mm)
ΔE_{fan}	difference in the fan energy use between cases 1 and 2 (kJ)
E_{fan}	fan energy use (kJ)
E_{equip}	natural gas use of chillers and boilers to satisfy the energy need for conditioning OA (m^3)
Cap_{equip}	capacity of chillers and boilers (MJ/h)
$E_{equip\_full\text{-}load}$	natural gas use of chillers and boilers in full-load operations (m^3/h)
$Cost_{energy}$	energy costs (Korean won)
$UnitPrice_{gas}$	natural gas unit price (Korean won/m^3)
$UnitPrice_{elec}$	electricity unit price (Korean won/kWh)

in annual energy costs resulting from the application of the TLVS and the consequent payback period.

Overview, examples, and existing research on TLVSs

Overview and examples of application

A TLVS, which is one of the energy-efficient ventilation technologies that use renewable geothermal heat, is a system that pre-cools or pre-heats ventilating OA through the exchange of heat between the OATL and the geothermal environment using labyrinth-shaped intake channels built into underground basement concrete structures. Although similar to an earth-tube ventilation system, which pre-cools or pre-heats OA by running the air through polyvinyl chloride (PVC) or metallic tubes buried in the ground outside buildings, a TLVS has advantages over an earth-tube ventilation system. For example, the intake air flow rates in a TLVS are high due to the large intake area. In addition, excavation is not required outside buildings to bury tubes because parts of the underground structure of the building itself are used as intake channels. Therefore, applications of the TLVS are expected to grow in the future. Table 1 compares the characteristics of the thermal-labyrinth and earth-tube ventilation systems.

TLVS technology has been used in a variety of energy-efficient buildings. One example is the TLVS (total length of 140 m) that was installed in the underground floor of the New Municipal Theater in Heilbronn, Germany. According to Daniels (1997), this system is capable of cooling and heating OA by 1–8 °C in the summer and 2–4 °C in the winter, respectively. Other examples of buildings using a TLVS include the Federation Square in Melbourne, Australia, the Research Support Facilities of the National Renewable Energy Laboratory in Golden, United States, the Planet Earth Gallery in Doncaster, United Kingdom, and the Institute for Global Environmental Strategies in Kanagawa, Japan.

Existing research

Based on their analysis of a TLVS in a complex building, Lee et al. (2005) reported that the required capacities of the heating and cooling equipment were significantly reduced during the operation of the TLVS. Min (2009) performed measurements inside a TLVS in the basement of a hypermarket, analyzed the cooling effect on the OA during spring (May) and summer (July), compared the measured data and the flow analysis results using the Fluent program, and reported that the cooling effect on OA increased proportionally as the temperature of OA increased. Son and Lee (2004) analyzed the thermal characteristics and the air flow patterns of a TLVS in the basement of a child welfare institution in Japan. Son and Park (2010) investigated a simplified method to predict the effect of cooling and heating by a system.

Similar studies on earth-tube ventilation systems have been conducted. Akridge (1980) reported that although its sensible cooling effect was adequate, an earth-tube ventilation system exhibited limited applicability in a hot and humid climate due to insufficient dehumidification. Al-Ajmi et al. (2006) analyzed the cooling effect of an earth-tube ventilation system in a desert area and verified the effect by comparing it with measured data. Lee and Strand (2008) used the EnergyPlus program to analyze the cooling effects of earth-tube ventilation systems and reported a substantial impact of the soil and climate conditions on system performance.

Analysis of the annual energy performance of a TLVS

Overview of the analyzed TLVS and the measurements

Analyzed TLVS

The analyzed building, the Ewha Campus Center shown in Fig. 1, is an educational, research, and welfare facility that was designed by French architect Dominique Perrault and was completed in May 2008; it is 68,657 m^2 in gross area and has 6 levels belowground and 1 level aboveground. As indicated in Fig. 2, the entire west and east sides of the 6-story building are underground. The underground walls are composed of 2 layers, and the space within the double-layer walls is used for the TLVS. As shown in Fig. 3, there are 9 zones of the TLVS, which operate independently. This study measured 1 of the 5 zones in the west side of the building (indicated by the circled area in Fig. 3).

As indicated in Fig. 4, the measured TLVS consists of an OA intake tower, a horizontal duct (total length of 288 m, width of 1 m, and height