DEPARTMENT OF MECHANICAL & AEROSPACE ENGINEERING

University of Strathclyde Engineering

ESRU Technical Report

Report for performpipe

Evaluation of Insulation Materials on Air-Source Heat Pump Performance in a Domestic Application

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Background

In the transition toward low-carbon heating systems, heat pumps have become central to residential energy strategies. However, their performance is sensitive to losses within the distribution system, especially in pipework that transfers heat between the unit and domestic storage. These losses reduce overall system efficiency and increase energy demand.

To address this, pre-insulated pipes are commonly used in retrofit and new-build applications. Their effectiveness, however, depends heavily on the insulation material's thermal conductivity. Materials with lower conductivity reduce heat loss more effectively, enhancing performance and reducing operating costs. Aerogel-based insulation is particularly promising due to its low thermal conductivity and compact profile.

This study was initiated in collaboration with PerformPipe, a manufacturer of aerogel-insulated pipes, to explore how different insulation materials compare in real-world conditions. It evaluates the thermal and operational impact of these materials within a domestic heat pump system.

Introduction

This report investigates how the thermal conductivity of pipe insulation affects the performance of a residential air-source heat pump system. Using dynamic simulation, the study evaluates a typical Scottish terraced house occupied by three individuals. The heat pump supplies domestic hot water via pre-insulated pipes exposed to both external and internal conditions.

The core objective is to compare the thermal and energy performance of various insulation materials, all of equal thickness, under identical operating scenarios. The focus is on quantifying differences in heat loss, energy consumption, and installation impact. Special attention is given to aerogel insulation, used as the reference for benchmarking.

Methodology

This study employed a dynamic whole-building simulation to evaluate the impact of different pipe insulation materials on the thermal and energy performance of an air-source heat pump (ASHP) system. The simulation was carried out using historical weather data typical of Edinburgh, Scotland.

The model represents a standard UK terraced house. Domestic hot water demand was based on usage patterns of a small family of three. The thermal system includes an ASHP unit with a compressor rated at 2 kW and a coefficient of performance (COP) in the range of 2.5 to 3.0 under typical operating conditions.

The heating system includes a thermal storage tank maintained at a nominal temperature of 55°C. The tank temperature was allowed to fluctuate dynamically based on heat demand and supply, simulating realistic control behaviour. The system includes a pre-insulated pipe loop connecting the heat pump to the storage tank. A total of 20 meters of piping was modelled: 10 meters exposed to external environmental conditions (5 meters supply and 5 meters return), and 10 meters located indoors. Figure 1 shows the digital twin model of a domestic dwelling with a heat pump used to provide heating, while Figure 2 shows a schematic diagram of the heat pump thermal distribution network used in the simulation.

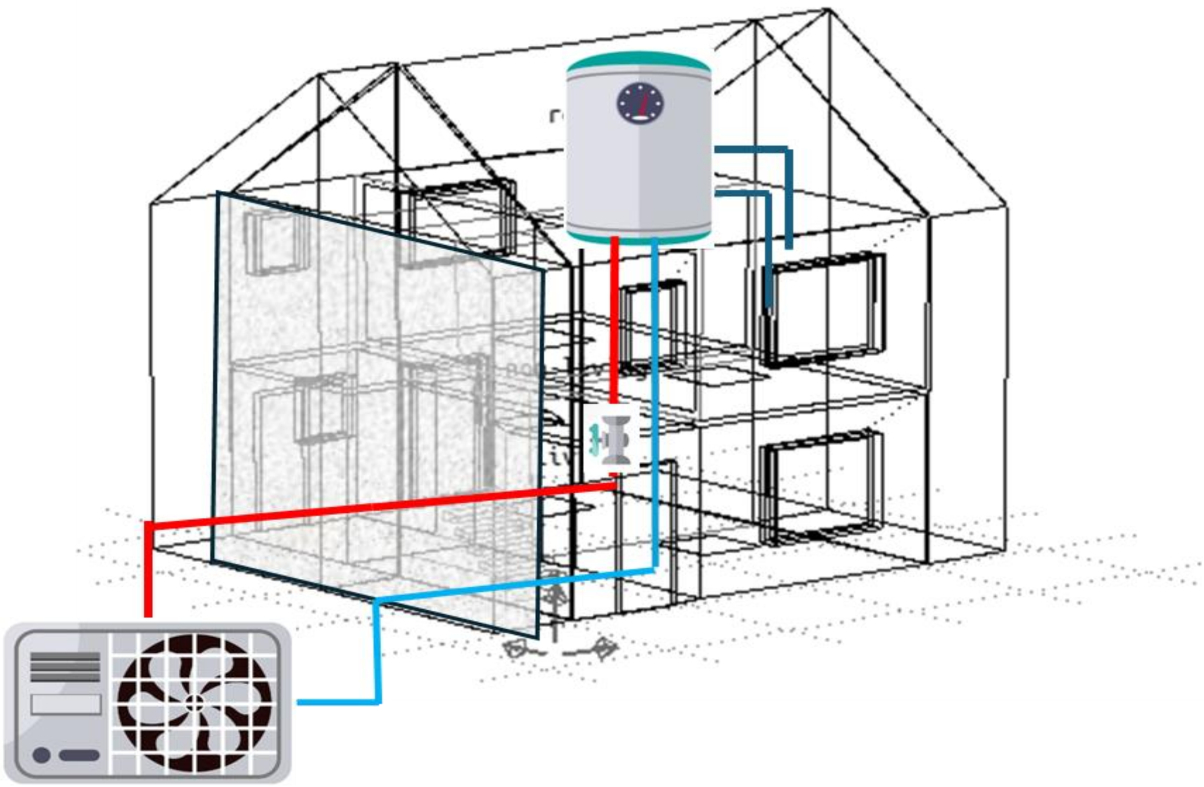

Figure 1 A digital twin model of a domestic dwelling with a heat pump used to provide heating

The primary focus was to evaluate how different insulation materials with the same thickness (12 mm) affect thermal losses, system energy use, and operating costs. A like-for-like comparison was performed, holding insulation thickness constant while varying thermal conductivity values. This allowed isolating the influence of thermal performance without introducing dimensional or installation biases.

The materials investigated are listed in the following table:

Table 1Investigated material with its corresponding thermal conductivity [1,2,3]

Insulation material	**Thermal conductivity (W/mK)**
PerformPipe (aerogel)	0.0175
Polyethylene (higher density)	0.033
Polyethylene (lower density)	0.037

Mineral wool	0.04
Cellular glass compressible	0.045
Cellular glass (20% deteriorated)	0.298

PerformPipe uses aerogel, a proprietary solution provided by the industrial partner, served as the benchmark due to its superior thermal performance at low thicknesses. The simulation explored how each material influenced key performance indicators such as the number of operating hours of the heat pump, total thermal output, annual electricity consumption, and resultant energy costs.

All simulations were performed under identical boundary conditions to ensure comparability and isolate the thermal conductivity effects. Performance metrics were normalized and compared as percentage deviations from the Aerogel reference case. Economic cost of electricity based on an average tariff of £0.28 per kWh.

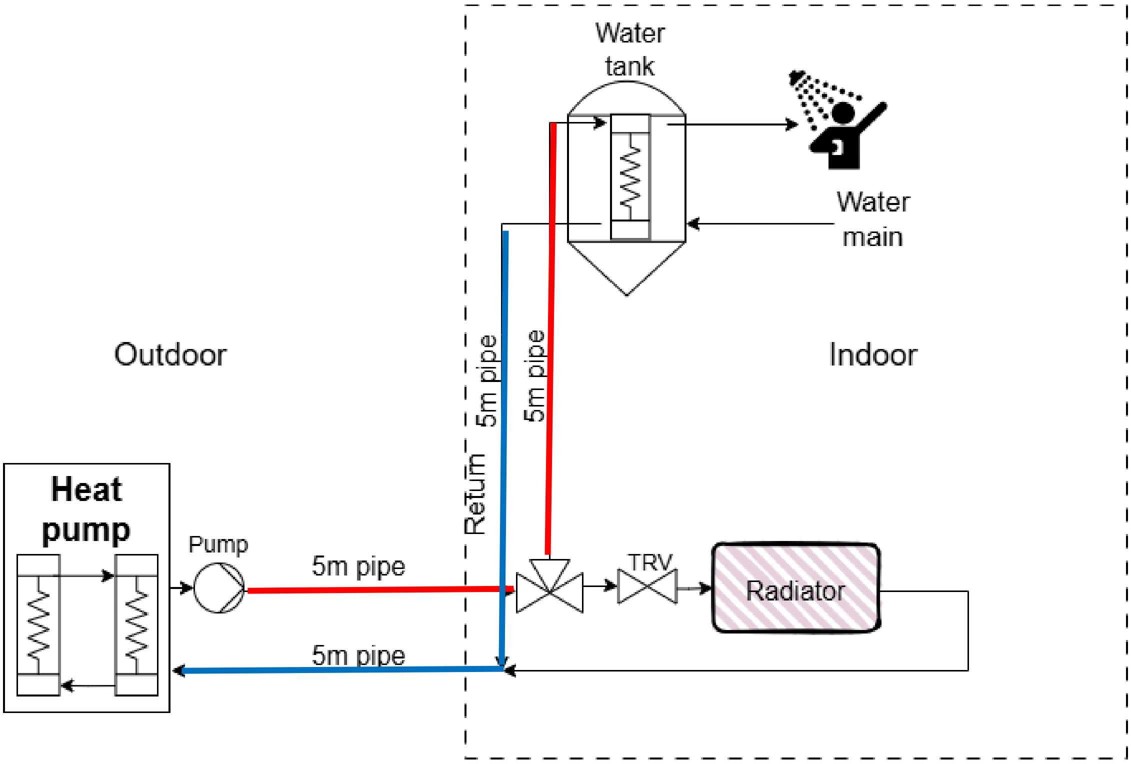

Figure 2 A schematic showing the system including the air to water heat pump and the insulated pipes outdoor and indoor

Results

As shown in the simulation results summarized in Figure 3 and Table 2, insulation materials with higher thermal conductivity increased both the operational hours of the heat pump and the associated electricity demand. This directly translated into higher energy costs. PerformPipe exhibited the lowest energy use and heat loss, confirming its superior performance under identical thickness constraints (12mm). The base case with PerformPipe insulation showed the lowest heat pump operational time (447.82 hours/year) and heat output (2994.54 kWh/year). In contrast, the system with deteriorated cellular glass required 585.72 hours/year a 30.79% increase in operating time and a heat output of 3930.97 kWh/year.

Heat losses for other materials increased proportionally with their thermal conductivities. For instance, polyethylene (higher density) foam increased heat loss by 14.75% compared to Performpipe, while deteriorated cellular glass insulation resulted in a 31.27% increase.

Electricity consumption followed the trend in heat losses. While polyethylene (higher density) foam and polyethylene (lower density) caused increases of 14.35% and 17.64% respectively. The highest electricity use (1663.50 kWh/year) was associated with the deteriorated cellular glass scenario, reflecting a 30.70% increase over the Performpipe case.

The increased electricity consumption translated directly into higher energy costs. Materials such as Polyethylene and cellular glass (20% deteriorated) showed cost increases in the range of £50–100 per year.

Table 2 Overview of the results comparison between the different insulation

Like for like bases comparison, 12mm thickness	number of hours HP ON	Increased on time (%)	Total heat output kWh per year	Heat losses increase compared to PerformPipe	Increased heat loss (%)	Total electricity use per annum (kWh/annum)	Increased electricity use (%)	Electricity cost based on average £0.28/kWh	extra cost in £ compared to aerogel	Increased energy costs (%)
PerformPipe	447.82	-	2994.54	-	-	1272.77	-	356.37	-	-
Polyethylene_H	512.63	14.47	3436.25	441.72	14.75	1455.39	14.35	407.51	51.13	14.35
Polyethylene_L	527.33	17.76	3535.67	541.13	18.07	1497.29	17.64	419.24	62.87	17.64
mineral wool	538.10	20.16	3609.30	614.76	20.53	1527.97	20.05	427.83	71.46	20.05
cellular glass compressible	555.78	24.11	3729.39	734.85	24.54	1578.85	24.05	442.08	85.70	24.05
cellular glass 20% deteriorated	585.72	30.79	3930.97	936.43	31.27	1663.50	30.70	465.78	109.40	30.70

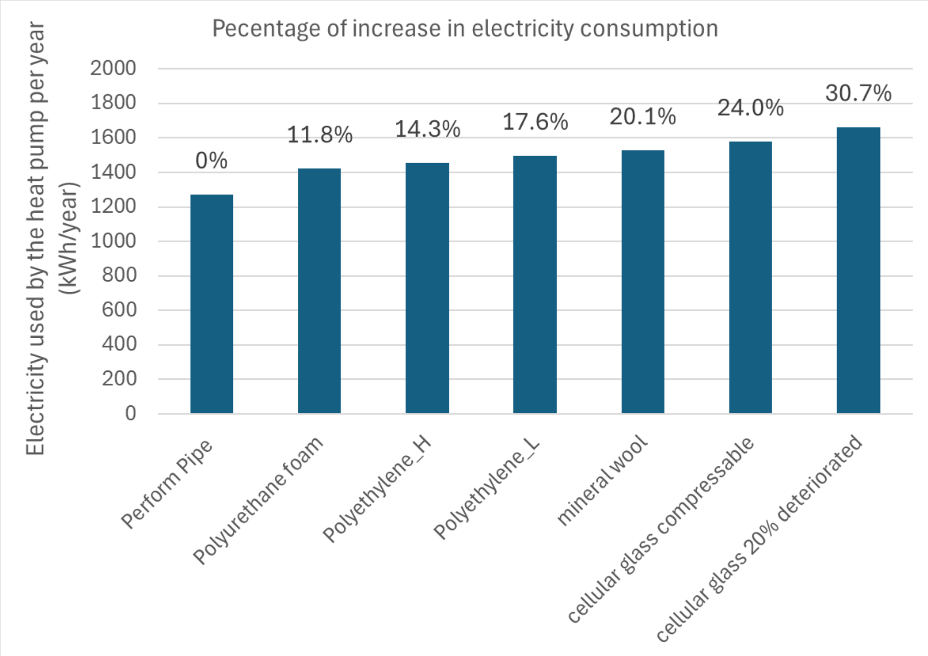

Figure 3 The predicted electricity consumption of the heat pump and the percentage increase relative to the PerformPipe are presented below.

The temperature drop of water flowing through various insulated pipes was evaluated under consistent boundary conditions. A constant flow rate of 0.333 kg/s, with water entering the pipe at 55°C and exposed to an ambient temperature of 8°C. Table 3 reports the UA values for each type of insulated pipe, along with the corresponding heat loss and the estimated outlet water temperature. UA (W/K) represents the overall heat transfer conductance based on the external surface area of the pipe. The pipe dimensions used in the analysis were a diameter of 52 mm including the insulation and a length of 5 m. Since matching conditions could not be fully reproduced in the dynamic simulation, the values were recalculated using a simplified steady-state heat loss model. This approach provides a reasonable estimate of the potential temperature drop across each pipe configuration and serves as an indicative comparison of their thermal performance.

$$Qloss = UA * (T_{water} - T_{ambient})$$

$$\Delta T = {}^{\dot{m}Cp}/_{Qloss}$$

Table 3 Comparison of Heat Loss and Temperature Drop Across Insulated Pipe Types at Fixed Flow Conditions

Insulation material	**UA (W/K)**	**Qloss(W)**	**Drop in temperature (°C)**
PerformPipe (aerogel)	0.8324	39.12	0.028
Polyethylene (higher density)	1.487	69.9	0.05
Polyethylene (lower density)	1.645	77.33	0.055
Mineral wool	1.761	82.77	0.06
Cellular glass compressible	1.948	91.6	0.066

In addition to the thermal performance, another critical parameter evaluated was the spatial implication of using alternative insulation materials. Maintaining the same U-value (1.02 W/m²K) required increasing the insulation thickness for materials with higher thermal conductivity. This increase, in turn, led to a larger external pipe diameter, which has practical implications during retrofit projects particularly when core-drilling through walls.

Table 3 summarizes the required insulation thickness and corresponding pipe diameters necessary to achieve the same thermal transmittance as the PerformPipe:

Table 4 pipe diameters necessary to achieve the same thermal transmittance

Insulation Material	Required Thickness (mm)	Pipe + Insulation Diameter (mm)	Cross-sectional Area (mm²)	Increase in Cross-sectional Area (%)
PerformPipe (aerogel)	12	52	2123.72	–
Polyethylene (High Density)	19.5	67	3525.65	66.01
Polyethylene (Low Density)	21	72	4071.50	91.72
Mineral Wool	23	74	4300.84	102.51
Cellular Glass (Compressible)	25	78	4778.36	125.00

Conclusion

Effective thermal insulation is essential for enhancing the performance of heat pump systems by reducing distribution losses, lowering electricity consumption, and minimizing operational costs. Among the materials evaluated, PerformPipe, featuring aerogel insulation demonstrated the best overall performance, offering the lowest heat losses and energy demand. This contributes not only to improved system efficiency but also to potential extensions in the lifespan of the heat pump due to reduced load cycles. In contrast, materials with higher thermal conductivity, especially those that degrade over time, significantly increase heat loss and energy use, leading to higher operational costs. Therefore, selecting high-performance insulation is a key factor in optimising both the technical and economic viability of heat pump installations.

References

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