Investigation of hydraulic imbalance for converting existing boiler based buildings to low temperature district heating

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Abstract

The hydraulic balance of heating network is considered as a pre-condition for the implementation of low temperature district heating (LTDH). Its imbalance result into high energy consumption and heat-losses in the network. In this study, a novel hydraulic model is presented which investigates hydraulic imbalance in the LTDH network, using real weather and hourly monitored operational heating data from an existing boiler based building. Analysis of delta t in space-heating system shows that the delta t is maximum when the outside air temperature is lowest and it decreases with increase in outside air temperature. Furthermore, the hydraulic imbalance is analysed for four different control scenarios with the aim to find an optimum scenario with minimum pumping power, energy consumption and heat-losses in the LTDH network. Results show that the hydraulic imbalance is due to the absence of flow-limiters and balancing valves on the return pipe and thermostatic radiator valves (TRVs) alone are unable to maintain hydraulic balance in the space-heating system of buildings. Moreover, the control scenario with variable flow-rate and fixed supply water temperature from the sub-station is found to be optimum. Compared to the constant flow-rate scenario, the pumping power, energy consumption and heat-losses in the LTDH network are reduced by approximately 2%, 63% and 14%, respectively.

Keywords: low temperature district heating, hydraulic imbalance, renewable energy, retrofitting of buildings, delta t, radiator connections

1. Introduction

With recent increasing environmental and energy efficiency concerns, maximising the efficiency of heating sector is thought as a key factor to foster future fossil-free energy policy. Recently, it is calculated that the heating sector represents 79% (192.5 Mtoe) of the final energy consumption in EU and district heating is considered as central towards sustainable energy system development [1, 2]. The United Kingdom represents second highest heat demand among other European countries [3]. The space heat and hot water is commonly supplied by individual gas-boiler in buildings and the share of district heating is currently less than 2% which

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can easily be increased up to 14% [4], especially in the central and south-eastern regions of the UK. The geographical distribution of heat demand in the UK is shown in Fig.1.

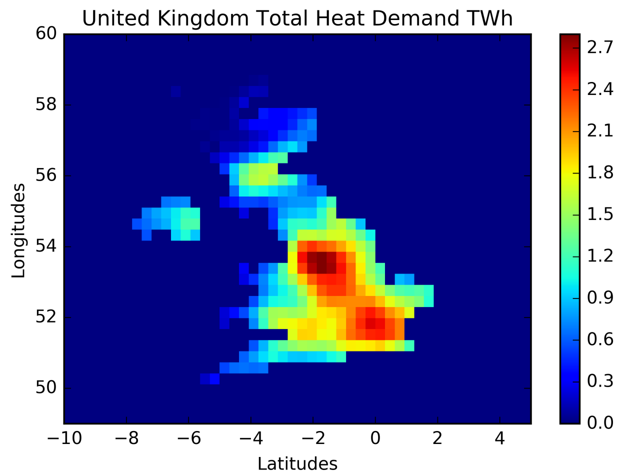

Figure 1: Geographical distribution of heat demand in United Kingdom at spatial resolution of 40 x 40 km^2 for the year (2011), taken from Ref. [5]. This illustrates that, the central and south-eastern regions of the UK have higher heat demand compared to other regions. This elaborates the significance of district heating in Nottingham and the case study used in this paper. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

The historical origin of district heating can be traced back to east-European countries and Russia (the former soviet union), where 1^{st} generation district heating was used as the communal heating source for buildings in densely populated areas. However, it did not prove to be successful due to the inefficient system and lack of control [6]. The same district heating technology and methodology was adopted by Scandinavian countries and district heating technology experienced rapid modernisation with higher efficient systems [6, 7]. The district heating has four generations and the major difference among these 1^{st} to 4^{th} generation is reduction in the supply water temperature from $\geq 200^o$C to $< 60^o$C [7]. The 4^{th} generation district heating is also known as low temperature district heating (LTDH). It's main characteristic is to decrease supply and return water temperature of the district heating to 60^oC and 30^oC, respectively. This makes the integration of renewable energy sources possible into the heat network.

Although, several studies have demonstrated the benefits of district heating and low temperature district heating, it still faces serious challenges which act as a barrier towards the transition to LTDH [8]. Several authors have identified these challenges as, maintaining high difference between the supply and return water temperature i.e delta t (Δt), hydraulic imbalance [9], optimisation of the demand driven system [10] and the legionella growth [11, 12]. Østergaard et al. [13] and Tunzi et al. [14] have discussed the importance of thermostatic radiator valves (TRVs) in maintaining high Δt in existing hydronic heating networks, and highlighted the problem of over-sized designing of space-heating system in existing buildings. Zhang et al. [15, 16, 17] have identified hydraulic imbalance as the main reason for over-heating in buildings and heat-losses in the Chinese district heating network. Yan et al. [18] evaluated the hydraulic performance of district heating network with several independent variable speed pumps. Wang et al. [19] presented a hydraulic model for optimising the district heating network economically.

The novelty of this study, compared to earlier studies, is to present the significance of using hourly monitored operational data from existing space-heating system for hydraulic imbalance investigation in the LTDH network. The LTDH is the most efficient district heating technology and requires precise designing. In this paper, a model has been developed in Python programming language to analyse the hydraulic imbalance in LTDH networks. The hydraulic imbalance problem leads to low Δt, high supply water temperature, flow-rate, pumping energy, energy and heat-loss across the heating network. Moreover, multiple years of monitored weather data is used to calculate energy savings from the renovation of buildings. This weather data is significant to this research as heat losses in the district heating network and space heat demand inside the apartment depends on it. These monitored weather data and operational data from an existing boiler based building before the conversion to LTDH are used for the analysis and results are compared for different operational scenarios.

The flow of this study is as follow: firstly the methodology for heat demand and hydraulic modelling is discussed in Section 2, then the LTDH intervention in Nottingham is presented as a case study in Section 3. Subsequently, the real hourly monitored weather data and operational space-heating system data of an existing boiler based building are discussed in Sections 4.1 and 4.3.1, respectively. Later, the hydraulic performance of LTDH network is analysed by assuming four different operational scenarios in Section 4.3. Finally, results for the optimum scenario, along with recommendations for the future LTDH network are given in Section 5.

2. Methods and modelling

The hydraulic performance modelling of the heating network is divided into two parts namely, heat demand modelling and hydraulic modelling. The heat demand modelling is performed by modelling the building in IDA-ICE software and calculations are performed using real monitored weather data. The hydraulic performance is evaluated using a mathematical hydraulic model developed in Python programming language. This provides necessary customisation and flexibility in implementing various thermal models for the analysis.

2.1. Heat demand modelling

The building is modelled in IDA-ICE 4.6.2 for heat-load estimation. IDA-ICE is a dynamic multi-zone simulation software commonly used by researchers and consultants [20]. This software is validated in-conformance with the standard DS/EN 15265 [21, 22] and uses an advanced algorithm for calculating energy performance of buildings using dynamic methods. The building geometry is first modelled using it's parameters such as, orientation, exposed perimeters and U-values. Then, the design conditions are set according to the standard [23] with the outdoor temperature of -8^{o}C for extreme events [24]. Subsequently, the detailed dynamic simulations are performed using weather data for Nottingham.

The heat demand depends upon outside weather conditions, therefore three years (2014-2016) of meteorological data is taken from weather station located in proximity to the case-study building used in this research at 53°3′41.62″ N, 0°57′49.75″ W . This meteorological data having temporal resolution of 15 minutes is first averaged into hourly mean values and then, converted into EnergyPlus format (*.epw*) weather file. This weather file is imported into IDA-ICE for heat demand estimation.

The thermal characteristics of the building are calculated using weather data from *.epw* climate file to maintain the indoor air temperature of 19^{o}C in every zone. The natural ventilation is taken as 0.94 ac/hr. This is standard minimum required ventilation in domestic buildings and in-accordance to the CIBSE Building Code [25]. The occupants' activity and house-hold equipment utilisation are taken on weekly schedules and the heat gains are assumed as for the domestic building conditions i.e. 0.81 and 1.55 W/m^2, respectively [14].

2.2. Hydraulic modelling

The hydraulic model of district heating network is developed with few following assumptions. This is to reduce the computational time without significant loss of accuracy.

- The water is in-compressible.
- There is no leakage in pipes.
- The supply water and return water pipelines are symmetrical.

The first step in hydraulic modelling is calculating required flow-rate, flow velocity in district heating pipes. This is done by calculating mass flow-rate (m) in each district heating pipe from the Eq.(1). The density (ρ) and specific heat (C_p) of water decreases with increase in water temperature. These are calculated using Eqs.(2) and (3) to get accurate results.

$$m = \frac{Q}{C_p(T_s - T_r)} \tag{1}$$

$$\rho = 1000.6 - (0.0128 * T_{water}^{1.76}) \tag{2}$$

$$C_p = 4209.1 - (132.8 * 10^{-2} * T_{water}) + (143.2 * 10^{-4} * T_{water}^2) \tag{3}$$

where Q is the heat load, T_s and T_r are the supply and return water temperature in each pipe, respectively. The flow-velocity in each pipe is calculated from mass flow-rate as the diameter of pipes is already known. However, the maximum allowable flow-velocity is always kept less than or equal to 2 m/s, as recommended in the design code standard [25]. The flow-rate (q) is limited according to the design values by modelling control valves in the heating network. The control valves regulate flow across the valve to required value by changing its opening. The flow-rate through the control valve for a given pressure drop (ΔP) is calculated as

$$q = K_v \sqrt{\Delta P_v} \tag{4}$$

K_v is the flow capacity of valve and ΔP_v (bar) is the controlled differential pressure across the valve. The head-loss (Δh_f) in pipes is estimated by Darcy equation [26].

$$\Delta h_f = \frac{8.f.l.q^2}{\pi^2.d^5.g} \tag{5}$$

l is the length of pipe, d is the diameter of the pipe and f is the friction factor estimated by Swamee-Jain equation [27].

$$f = \frac{0.25}{\left[log\frac{e/d}{3.7} + \frac{5.74}{Re^{0.9}}\right]^2} \tag{6}$$

where e is the roughness of inner pipe surface. Re is the Reynold number of flow in the pipe. The flow-rate in each pipe is calculated using principles of fluid dynamics from Ref. [27].

2.2.1. Energy consumption calculation

The pumping power (P_a) and electricity consumption (E) of the heating network are calculated using Eqs. (7) and (8).

$$P_a = \frac{\rho.g.\Delta h_f.q}{\eta} \tag{7}$$

$$E = \frac{S * P_a}{\eta_m} \tag{8}$$

where P_a is the shaft pumping power, g is the gravitational constant, S is the security factor taken as 1.1, η and η_m are the efficiency of pump (0.85) and electric motor (0.70), respectively.

2.2.2. Thermal resistance of pipes and heat-loss calculation

The estimation of heat-losses from pipes is important while designing the district heating network. The proportion of heat-losses determine the supply and return water temperature as well as flows in the district heating network. In this study, a thermal resistance model is implemented for calculating distribution heat-losses and outlet water temperature from each pipe.

The thermal resistance depends on the composition material of pipe, ground surrounding the pipe and temperature difference. The thermal resistance of pipe's steel mantle is ignored as it's negligible compared to other resistances. The thermal resistance of insulation (R_i) and ground (R_g) is calculated considering thermal conductivity of respective materials [28]. Furthermore, the thermal resistance (R_h) is due to heat transfer between the supply and return district heating pipes, which are usually identical. These thermal resistances are defined as,

$$R_i = \frac{1}{2\pi\lambda_i} * ln\left(\frac{D_m}{D_o}\right) \tag{9}$$

$$R_g = \frac{1}{2\pi\lambda_g} * ln\Big(\frac{2H}{D_m} + \sqrt{\Big(\frac{2H}{D_m}\Big)^2 - 1}\Big) \tag{10}$$

$$R_h = \frac{1}{2\pi\lambda_g} * ln\Big(\sqrt{\Big(\frac{2H}{S_c}\Big)^2 + 1}\Big) \tag{11}$$

The thermal conductivity of PEX insulation foam (λ_i) usually varies between 0.024 - 0.026 W/m^{o}C [29] and depends upon several factors such as, temperature, moisture and degradation of insulation material. The thermal conductivity (λ_i) is calculated using following relation from experimental results in Ref. [30]. This relation considers variation in water temperature to get accurate results.

$$\lambda_i = 0.0196734 + 0.000080747303 * T_{water} \tag{12}$$

The thermal conductivity of ground (λ_g) is taken constant. The effective burial depth (H) is the resistance between air and ground due to convective and radiation heat transfer [28, 31].

$$H = S_d + 0.0685 * \lambda_g \tag{13}$$

S_d is the depth of pipe from soil level, $S_c = L_c{+}Dm$. L_c is the distance between supply and return pipe and D_m is the pipe diameter. The thermal resistance due to interaction between three sections, water-insulation (R_{wi}), ground-surroundings (R_{gu}) and insulation-ground (R_{ig}) is determined using following equations [28].

$$R_{wi} = \frac{1}{2\pi\lambda_i} * ln\left(\frac{1 + \frac{D_m}{D_o}}{2}\right) \tag{14}$$

$$R_{gu} = \frac{1}{2\pi\lambda_g} * ln\Big(\frac{4H}{D_m + D_g} + \sqrt{\Big(\frac{4H}{D_m + D_g}\Big)^2 - 1}\Big) \tag{15}$$

$$R_{ig} = R_i + R_g - R_{wi} - R_{gu} \tag{16}$$

These results are then scaled to get actual steady state heat-loss [28] using the factor (θ).

$$\theta = (R_i + R_g)\frac{(R_i + R_g) - \gamma R_h}{(R_i + R_g)^2 - R_h^2} \tag{17}$$

$$\gamma_{supply} = \frac{\Delta T_r}{\Delta T_s} = \frac{T_{rp} - T_u}{T_{sp} - T_u} \tag{18}$$

$$\gamma_{return} = \frac{\Delta T_s}{\Delta T_r} = \frac{T_{sp} - T_u}{T_{rp} - T_u} \tag{19}$$

T_u is the soil temperature, γ_{supply} for supply pipe, is the ratio between return water temperature (ΔT_r) and supply water temperature (ΔT_s). Moreover, γ_{return} for return pipe, is the inverse of γ_{supply}. Combining all above equations provide the total heat transmission resistance (R_{total}) and overall heat transfer coefficient (U).

$$R_{total} = R_{wi} + R_{gu} + R_{ig} \tag{20}$$

$$U = \frac{1}{R_{total}}\theta \tag{21}$$

Finally, the heat-loss (Q_{loss}) and outlet water temperature from each pipe (T_{outlet}) [32] is calculated as,

$$Q_{loss} = U * l * (T_{supply} - T_u) \tag{22}$$

$$T_{outlet} = (T_{inlet} - T_u)exp^{-\frac{U.l}{C_p.m}} + T_u \tag{23}$$

The Eq.(23) represents the outlet water temperature from each pipe section is directly proportional to the mass flow-rate (m) and inversely proportional to the length (l) as well as overall heat transfer coefficient of the pipe (U). T_{inlet} is the inlet water temperature from the previous pipe and T_{outlet} is the outlet water temperature to the next pipe.

3. Case study: low temperature district heating intervention in Nottingham

Nottingham is located in the eastern region of England known as East-midlands. It is the seventh largest metropolitan economy in the United Kingdom and ninth largest city having population of around 321,550. This city has the largest district heating network in entire UK, connecting approximately 4,900 domestic and commercial users [33] in the city centre. This 68 Km of well-insulated district heating pipe network relies on heat from the waste-incinerator, which generates 442 - 476 GWh of heat annually and provides steam to the combined heat and power (CHP) plant. The pressurised hot-water from CHP plant enters the district heating network at a rated pressure and supply water temperature of 11 bar and 140^{o}C, respectively.

The heat-generation and distribution in Nottingham has very high amount of heat-losses. Though, the waste-incinerator generates 442 - 476 GWh of heat annually, only 144 GWh of heat is used for distribution. The seasonal variation of supply water temperature is between 85 - 120^{o}C. Ianakiev et al. [33] have discussed that almost 21% of heat is wasted during heat transmission from waste-incinerator to the CHP plant, and 36 % during electricity generation at the CHP plant as flue-gases. The CHP plant makes both networks inter-related i.e. electricity and district heating network. However, if these losses are reduced, then more electricity can be generated. The current network operates with following priority:

1. Burning of waste in waste-incinerator.
2. Electricity generation.
3. Heat for the heating network.

The district heating is significant to the city, especially with it's recent ambitious targets of achieving 20% of energy from renewable energy and 26% reduction in CO_2 emissions by the year 2020. The waste incinerator already burns annual waste of around 170,000 tonnes and the district heating scheme offsets approximately 27,000 tonnes of CO_2 emissions annually [33].

A district heating network involves two sections, primary heating network and secondary heating network. The primary heating network in Nottingham has a CHP plant as heat source, which provides hot water through the pipe network and several sub-stations. The secondary heating network is the heat distribution network from sub-station to the buildings. This paper considers a low temperature secondary heating network from the REMOURBAN project in Nottingham, where return water pipe (60^oC) of the existing district heating network is to be used as source for new LTDH network (60/30). In this study, the aim is to reduce heat losses and evaluate hydraulic performance under different operational scenarios for this planned LTDH network (60/30). This secondary LTDH intervention for 94 flat consumers is first of it's kind in the UK, which utilises return water pipe of the district heating network. It has anticipated that this will provide a gateway to Nottingham in efficiency improvement and extension of existing district heating network as well.

4. Analysis and results

This section uses LTDH intervention in Nottingham as a case-study and compares results of this study for four different operational scenarios. The analysis is divided into two parts. First, the significance of retrofitting of buildings is discussed using monitored weather in Section 4.2. Then, the hourly monitored operational data is discussed in Section 4.3.1 and the hydraulic imbalance in existing space-heating system inside the building is analysed. Subsequently, these hourly monitored data-sets are used as input for the hydraulic model and the hydraulic performance for planned LTDH network is evaluated in Sections 4.3.2 and 4.3.3, respectively. Finally, results are compared for four different operational scenarios and recommendations for resolving hydraulic imbalance issue in LTDH network are described in Section 5.

4.1. Monitored weather data

The weather data is hourly mean of multiple years data. This is done to smooth-out the effect of extreme events, otherwise weather data for an individual year can have sharp peaks. The monitored weather data contains hourly outdoor temperature, wind speed, wind direction, soil temperature and solar radiations data. This data is first converted into Energy-plus climate file (*.epw*) and then imported into IDA-ICE software, as discussed above in Section 2.

It is observed in Fig. 2 that, the outside air temperature is rarely below 0^oC and varies between 2 - 10^oC in winters and 15 - 25^oC in summers. Moreover, Nottingham receives fairly significant amount of solar

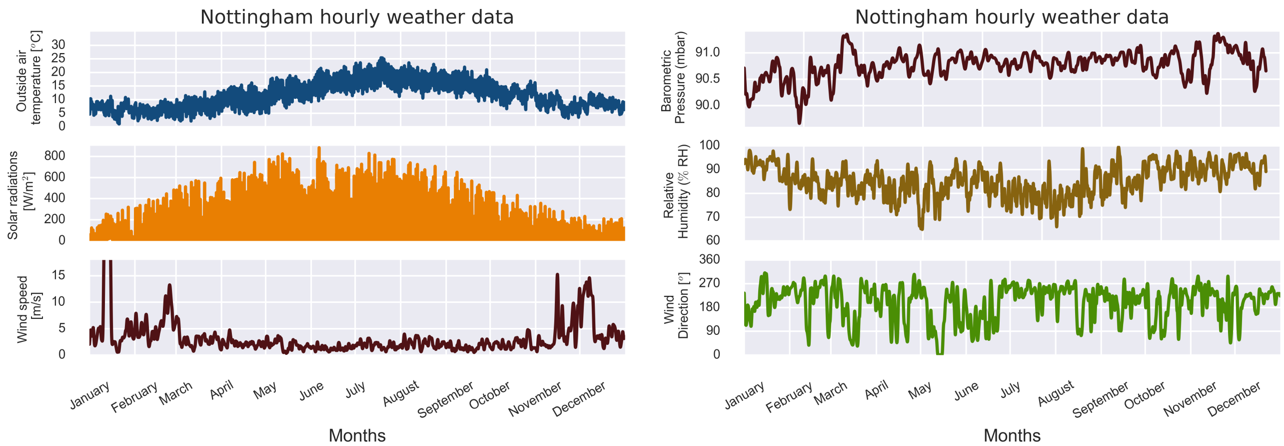

Figure 2: Hourly monitored weather data for Nottingham. This weather data is used for heat demand estimation. The heat demand in buildings depends upon outside weather conditions, therefore three years (2014-2016) of meteorological data is taken from the weather station located at 53°3′41.62′′ N, 0°57′49.75′′ W.

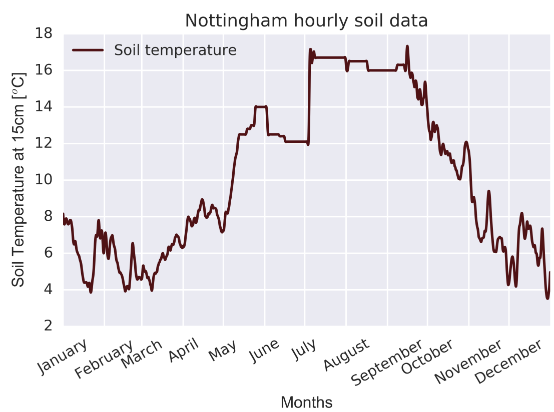

Figure 3: Hourly monitored soil temperature data of Nottingham, measured at 15 cm depth. This data is hourly mean of three years (2014-2016) of meteorological data and taken from the weather station located at 53°3′41.62′′ N, 0°57′49.75′′ W. The soil temperature data is used for calculating outlet water temperature and heat-loss from district heating pipes.

radiations especially in months from April - September and the hourly solar radiations are up to 900 W/m^2. This elaborates the importance to consider solar radiations in heat demand calculations. Furthermore, the solar radiations and wind speed depict opposite trend to each other. The hourly wind speed is mostly smooth in summers and varies between 1 - 6 m/s. However, it fluctuates considerably from December to February, with the maximum wind gust speed in January. This is the period when there are wind storms in the UK.

The hourly soil temperature is important for outlet water temperature and heat-loss from district heating pipes calculations. Fig. 3 shows that, the soil temperature varies between 8 - 16^{o}C in summers and 4 - 8^{o}C in winters, respectively. All these hourly monitored data-sets are used as input for heat demand and hydraulic modelling simulations of the LTDH network.

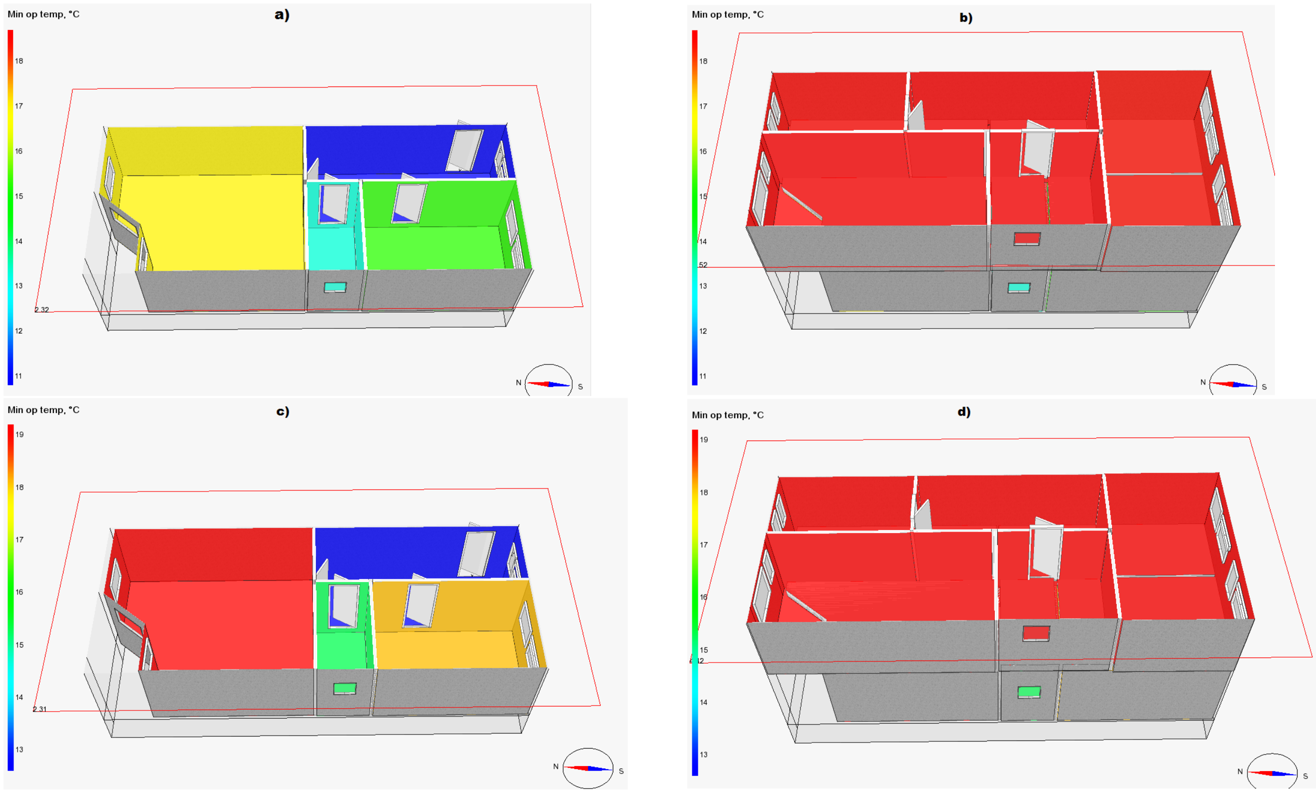

Figure 4: Simulation results from the IDA-ICE software. Figs.(a,b) show the minimum operative temperature before the retrofit and figs.(c,d) show minimum operative temperature after the retrofit.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

4.2. Heat demand after retrofitting of buildings

Improving the energy performance of existing buildings is a major corner-stone for moving towards low carbon economy, as 75 - 85% of existing building stock in the UK will still be operational by the year 2050 [33]. Moreover, retrofitting of buildings is necessary for the implementation of LTDH. In REMOURBAN Project, 94 flats will be deep-retrofitted with the aim to increase the energy performance of existing buildings. These 94 flats are in four blocks, constructed from 1960's.

In this analysis, one of the building from REMOURBAN project is used and heat demand is calculated for both pre-retrofit and post-retrofit conditions. The U-value for the walls, roof, floor, windows and other building material information is taken from the survey, as these buildings are part of social community housing where no construction plans were available. The pre-retrofit building has raft-foundations and constructed with brick cavity walls, concrete floor slabs, single glazing windows and roof covered with concrete tiles. These flats have been insulated to reach the minimum U-value for the brick cavity walls, windows and roof to 0.3, 1.8 and 0.123 W/m^{2}K, respectively. This post-retrofit condition is in accordance with the national standard for new building envelopes 'UK Building Regulation - Part L1B' [34]. The deep-retrofitting has energy savings closer to the normal retrofitting practice and improved the U-value with the insulation of walls, floor and glazing, as shown in Table 1.

The simulation results in Fig. 4 show that, the mean operative temperature for all zones is around 19^{o}C at the minimum outdoor air temperatures with exception for the entrance region. The lower mean operative temperature at main entrance of the flat is due to the infiltration and opening of the entrance door according to the schedule. The retrofitting has improved the upper-limit of air infiltration from 0.6 ac/hr (air changes per hour) to 1.0 under 50 Pascal [35]. It is calculated that, the major difference is noticed in the heat demand for the ground floor, where the mean operative temperature after the retrofit has increased from 17^o - 19^{o}C.

The post-retrofit annual energy demand for each flat has been reduced from 23,897 to 11,253 KWh. This reduction of almost 52% is achieved by just improving windows glazing from single to double glazed, walls and roof insulation. These results for the reduction in annual heat demand obtained from IDA-ICE software are comparable to the real monitored heat consumption. The specific room minimum operative temperatures for different zones are shown in Fig. 4.

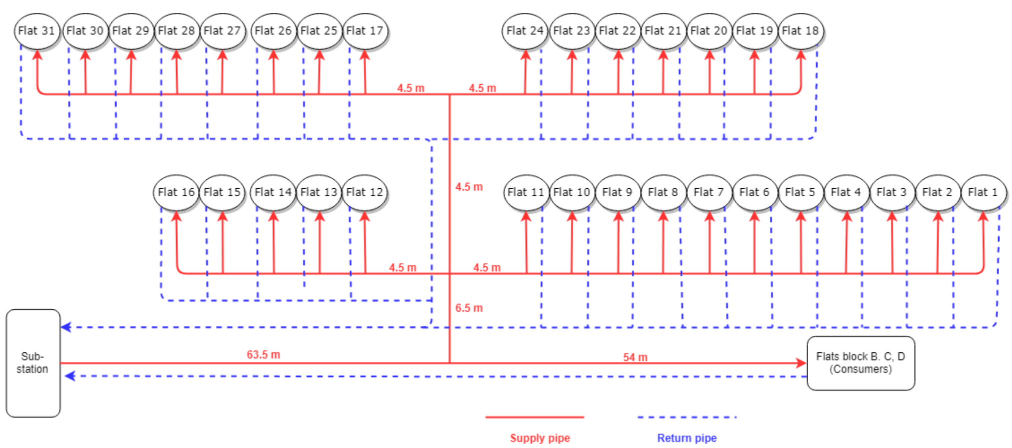

Figure 5: The main topology layout of the low temperature district heating network from REMOURBAN Project in Nottingham, UK.

4.3. Hydraulic analysis

The hydraulic balance of the space heating system is considered as a pre-condition for achieving high Δt. The hydraulic balance in a well-functioning heating network is maintained when the water flow in entire heating network is balanced. A low temperature heating network is in hydraulic balance when the flow-rate and difference between the supply and return water temperature i.e. Δt is in accordance to the consumer heat consumption in the heating network [9]. The hydraulic imbalance issue leads to lower efficiency, low

Δt and uneven distribution of heat in the heating network. This also leads to thermal comfort issues and over-heating in buildings due to excess heat, which make the residents to open windows. The heating network has optimal hydraulic performance when the energy consumption for fulfilling hydraulic head at consumers is lowest.

In this analysis, the hydraulic imbalance is investigated for 31 flats in a building which is to be converted to the LTDH. These 31 flats are out of 94 flats from the REMOURBAN project and shown in Fig. 5. All parameters for this small LTDH network are taken from the REMOURBAN project, as earlier discussed in Section 3. It is planned that, the network will operate at constant flow-rate and the secondary supply side of heat-exchanger in the sub-station will be without weather compensation control. The control valves will be installed at the connection point of each building, but there will be no balancing valves or flow-limiters installed on the return water pipe. The secondary supply water temperature in LTDH will be adjusted manually before the beginning of every season and and the indoor temperature control inside the flat is to be regulated by TRVs on radiators. Furthermore, there will be no changes in already installed space-heating system inside the flat, except replacing heat source from the gas-boiler to heat-exchanger of the LTDH network. The schematic of space-heating system loop inside the flat is shown in Fig. 6.

First, the operational space-heating system data from one of the flat installed with gas-boiler is used for understanding thermal comfort and hydraulic imbalance inside the building. Then, the hydraulic performance of this LTDH network is investigated by using hydraulic model developed in Section 2 and results are compared among four different operational scenarios. The model calculates flow-rate, head-loss at each flat as well as pumping power and energy consumption in the LTDH network. The scenarios 1 and 2 evaluate the LTDH network with constant flow-rate, whereas scenarios 3 and 4 are with variable flow-rate. The flow-rates, pumping power, energy consumption and heat-losses are compared among all scenarios and the optimum scenario is determined.

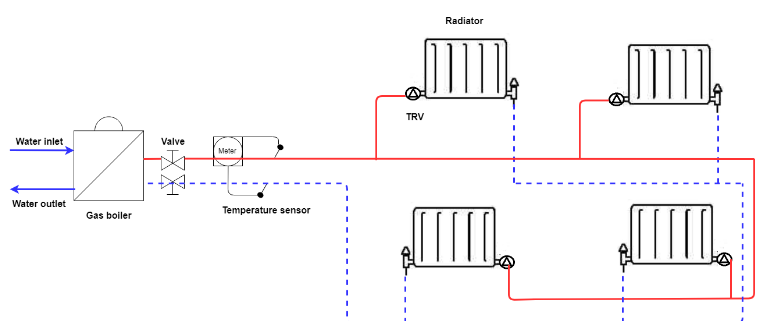

Figure 6: Schematic configuration of space-heating system loop inside the flat. The space-heating system is double string system with plate radiators and thermostatic radiator valves (TRVs).

4.3.1. Monitored operational space-heating system data analysis

The boiler based space-heating system in the UK buildings operate with constant flow-rate and the hydraulic balance is maintained by regulating supply water temperature according to the heat consumption.

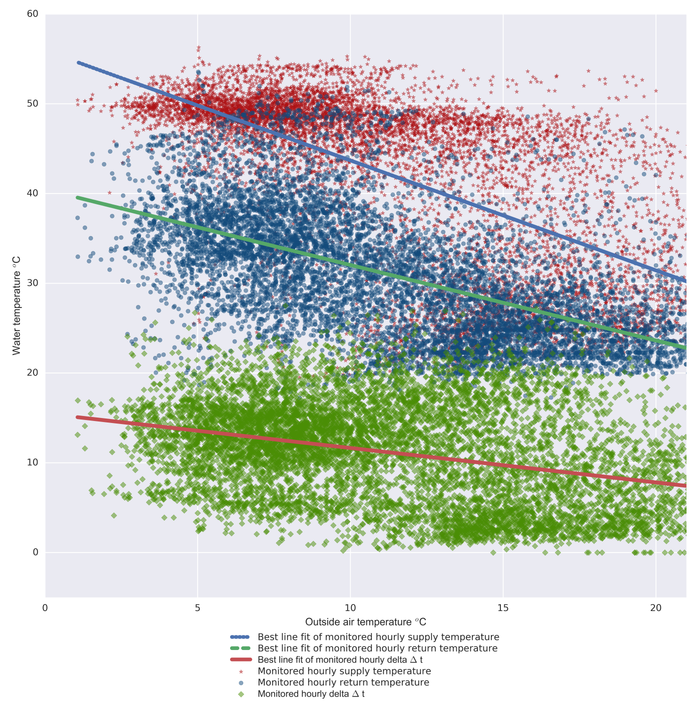

Figure 7: Real hourly monitored supply and return water temperature data of space-heating system from an existing boiler based building. The scatter plot presents the relationship between water temperature and outdoor air temperature. The best line fit of hourly monitored supply and return water temperature, depicts negative correlation between the water temperature and outside air temperature.This confirms the significance for regulation of return water temperature with respect to outside temperature for achieving high Δt.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

This approach is helpful in achieving the hydraulic imbalance, but impacts the Δt and overall efficiency of heating system. Nevertheless, the installation of TRVs on radiators somehow regulates the flow-rate with respect to indoor temperature, but the hourly monitored space-heating system data discussed below suggests that, the Δt still remains low.

The heat demand, supply and return water temperature data from the existing boiler based building is monitored for understanding current operation of the space-heating system, before it's conversion to LTDH. Each flat in the building is installed with individual gas-boiler for space-heating and the indoor room temperature is controlled by TRVs on radiators. The schematic of space-heating system loop inside the flat is shown in Fig. 6 and the power capacity of installed hydronic radiator in Table 2.

It is interesting to observe in Fig. 7, that the supply and return water temperature decreases with increase in outside air temperature. The Δt of space-heating system is highest when the outside temperature is at 0^{o}C and lowest at around 23^{o}C, respectively. The best line fit of hourly monitored supply and return water temperature, depicts negative correlation between the water temperature and outside air temperature. Moreover, the slope of supply water temperature is steeper than the return water temperature. This methodology for the evaluation of hydraulic imbalance has been adopted from Zhang et al. [10], where the best line fit also depicts the negative correlation.

Furthermore, the supply water temperature remains relatively smooth whereas, the return water temperature fluctuates by more than 20^{o}C for the same outdoor air temperature and consequently lowers the Δt. These variations in supply and return water temperature keeps the average Δt to just 11 throughout the year. Even-though, the network has been designed and configured for the Δt of 30. This further confirms that, the supply water temperature decreases rapidly with increase in outside temperature, than the return water temperature. These trends can be observed from the scatter plot in Fig. 7.

It is concluded that, the regulation of return water temperature with respect to outside temperature is more significant, than the supply water temperature for achieving high Δt. Moreover, these variations in return water temperature compared with supply water temperature at the same outdoor temperature, is due to the hydraulic imbalance in space-heating system. This is assumed due to lack of thermal comfort complaints reported by occupants during the heating season and the space-heating system operates at constant flow-rate. This hydraulic imbalance issue can be explained due to the over-sizing of room radiators and other control equipment inside the building.

The following scenarios use this hourly monitored space-heating system operational data and weather data from Section 4.1 for hydraulic calculations in the LTDH network. The control valve settings are kept same in all scenarios, as it provides the reasonable comparison among results.

4.3.2. Scenario 1 and 3 - constant supply water temperature

The supply water temperature in both scenarios 1 and 3 is kept constant from the sub-station at 60^{o}C. The flow-rate is constant in scenario 1, whereas it varies in scenario 3 with respect to the outdoor temperature using variable speed pumps and weather compensation control at the sub-station.

It is observed that, the energy consumption in scenario 3 reduces from 964 KWh to 360 KWh with variable flow-rate in the LTDH network. This reduction of almost 63% in scenario 3 by flow-rate variation suggests that variable speed pumps are more energy efficient, especially at partial heat consumption conditions. The variable speed pumps regulate the supply flow-rate from substation and more energy efficient. The head-loss at each flat in scenario 3 is lower compared to that in scenario 1, but it shows similar trend in both scenarios. The energy consumption and head-loss comparison in different operational scenarios is graphically shown below in Figs. 8, 9 and 10.

The heat-loss from district heating pipes in the LTDH network is almost same in both scenarios. This represents the strong dependence of heat-loss from pipes on supply water temperature, than the flow-rate. Even-though, the seasonal variation increases the soil temperature, but the heat-loss from district heating pipes remains pretty same throughout the year. Moreover, the flow-rate and pumping power are comparatively higher in summer. This is due to low Δt and shown in Fig. 11. The overall heat-losses in the LTDH network reduces from 62% to 47% in scenario 3. This reduction by almost 14% in scenario 3 suggests that the variable speed pump reduces the heat-losses but up to a certain limit. These results are compared graphically

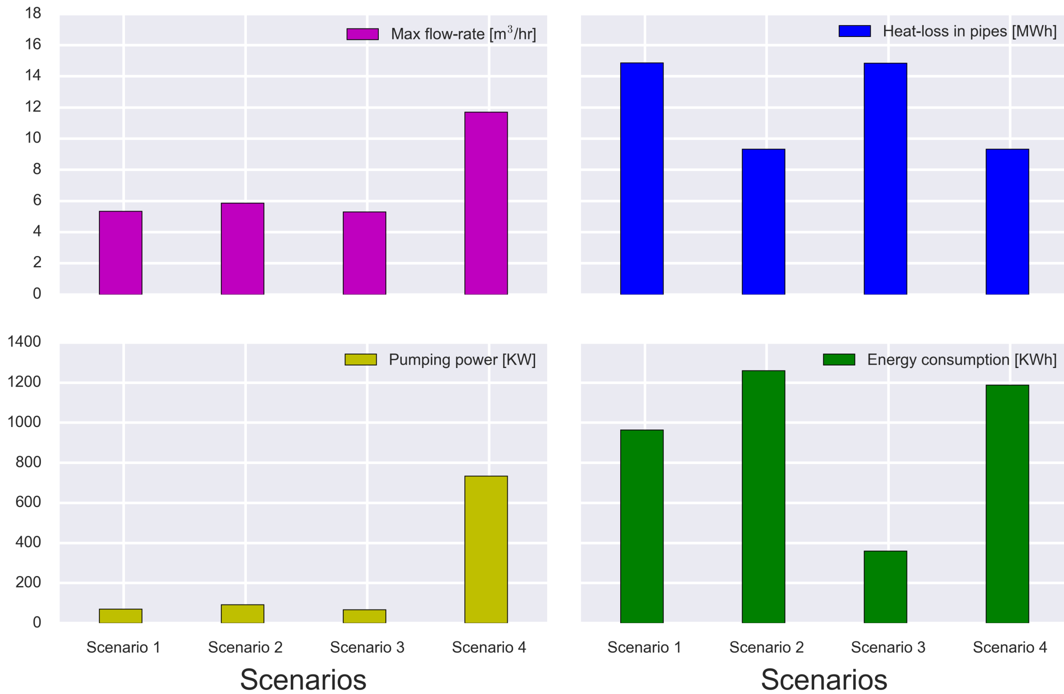

Figure 8: Comparison of results between different operational scenarios. First row represents maximum flow-rate from the plant room and heat-loss from district heating pipes in the ground during heat transmission. The second row represents pumping power and energy consumption of the LTDH network.

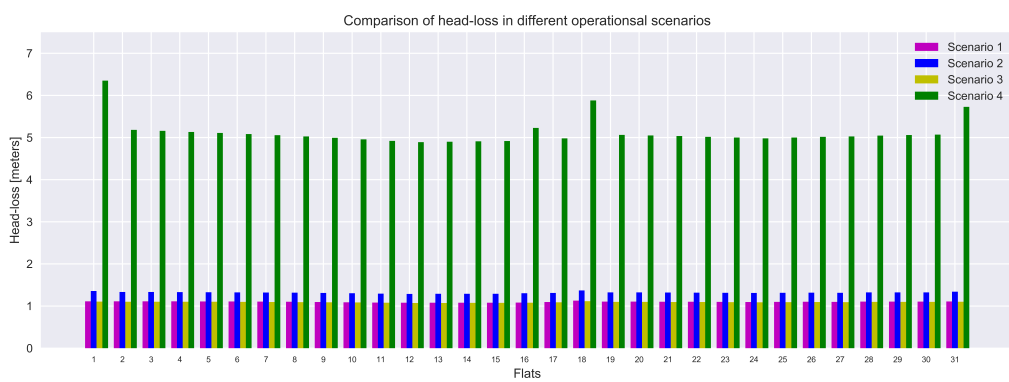

Figure 9: Head-loss comparison to each flat in different operational scenarios.

among scenarios 1 and 3 in Fig. 12 and further elaborated in Table 3.

4.3.3. Scenario 2 and 4 - variable supply water temperature

The scenario 2 and 4 apply when the supply water temperature varies with respect to outdoor temperature from the sub-station. The flow-rate is constant in scenario 2, whereas it's variable in scenario 4 using variable speed pumps in the LTDH network.

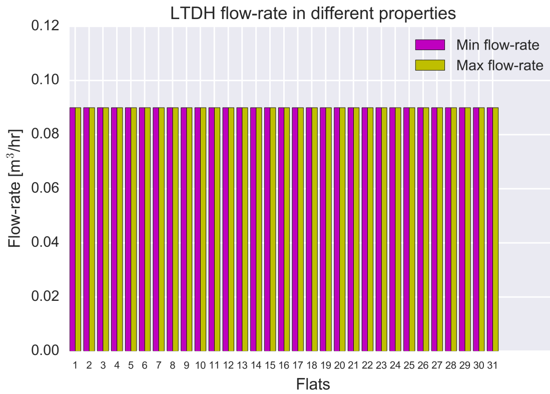

Figure 10: Figure represents the maximum and minimum flow-rate restricted to each flat using flow-rate control valves in the LTDH network.

It is found that the supply water temperature variation increases energy consumption considerably compared to scenario 1. The energy consumption increases from 964 to 1261 KWh, respectively. This 29% increase of energy consumption in scenario 2 and 22% increase in scenario 4 can be understood, as the flow-rate increases with reduction in supply water temperature from the sub-station. However, the head-loss in scenario 2 is comparable to scenario 1, but the pumping power increases by 32%. The flow-rate and head-loss in scenario 4 are both significantly higher compared with scenario 1. These energy consumption and head-loss results are shown in Figs. 8, 9.

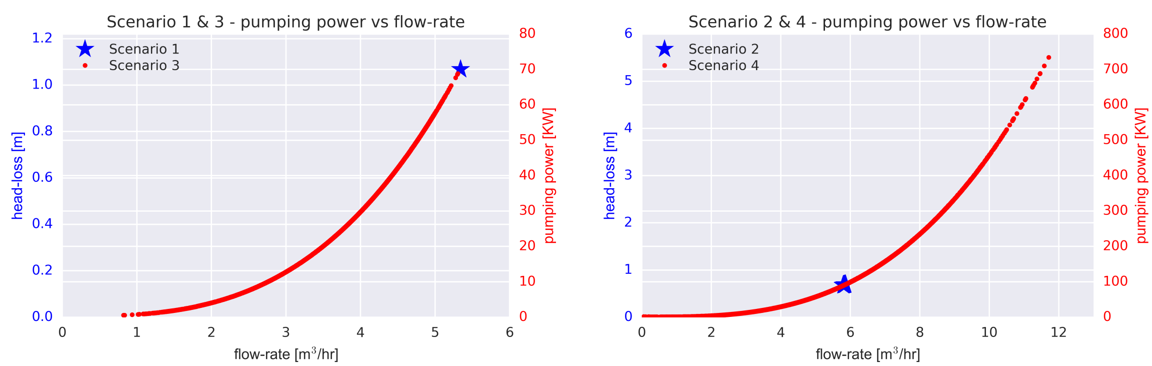

Figure 11: Pumping power with respect to flow-rate and head-loss for different operational scenarios. Left figure compares result for scenarios 1 and 3, whereas right figure compares result for scenarios 2 and 4.

It is observed that the heat-loss from district heating pipes in both scenarios reduces by 37%, and the heat-loss in scenario 4 is even lower than scenario 3. Nevertheless, the flow-rate and pumping power are comparatively higher in scenario 4. These results are shown in Figs. 11 and 12. It is concluded that, reducing supply water temperature is more effective compared with flow-rate variations for reduction in heat-losses in the LTDH network. The overall heat-losses in LTDH network in scenarios 2 and 4 are reduced

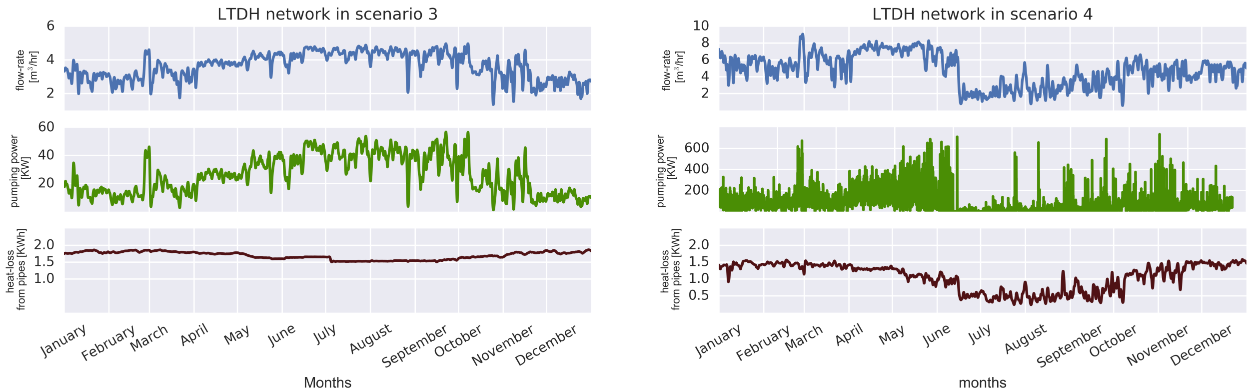

Figure 12: Comparison between the operational scenario 3 and 4. First and second row represents hourly flow-rate and pumping power from the plant room, whereas the third row represents hourly heat-loss from district heating pipes in the ground during heat transmission.

to just 9% and 11%, respectively. These heat-losses are minimal compared with other scenarios. These results, along with comparison are further elaborated in Table 3.

5. Discussion and recommendations

The district heating networks in the UK commonly operate with high supply water temperature and constant flow-rate, as fixed speed pumping is still preferred. This leads to high heat-losses in the district heating network. The efficiency of these heating networks can be improved significantly if the Δt is improved.

This study concludes that variable speed pumping with constant supply water temperature from the sub-station has the lowest energy consumption and should be adopted for the new LTDH networks, as explained in scenario 3. Whereas, the heat-losses in existing district heating networks which operate at constant flow-rate can be reduced significantly, if the supply water temperature is regulated according to the outside temperature. This can be done using weather compensation control at the sub-station and elaborated in scenario 2. Furthermore, lowering of supply water temperature significantly decreases heat-losses in the LTDH network and provides the opportunity to utilise renewable heat sources and other low-grade waste heat sources. But, it should be realised that, this will increase energy consumption in the LTDH network. The Fig. 8 shows the comparison between other operational scenarios.

The case study in Section 4.3.1 illustrates the hydraulic imbalance issue for a typical space-heating system in the UK, where only control valves are installed in the supply pipes and no balancing valves or flow-limiters are installed on the return pipes. It can be presumed that the absence of these valves creates the hydraulic imbalance, which leads to the low Δt and excessive heat-losses across the LTDH network. This is usually complimented with high supply water temperature from the sub-station, which leads to high heat-losses and high return water temperature in the heating network.

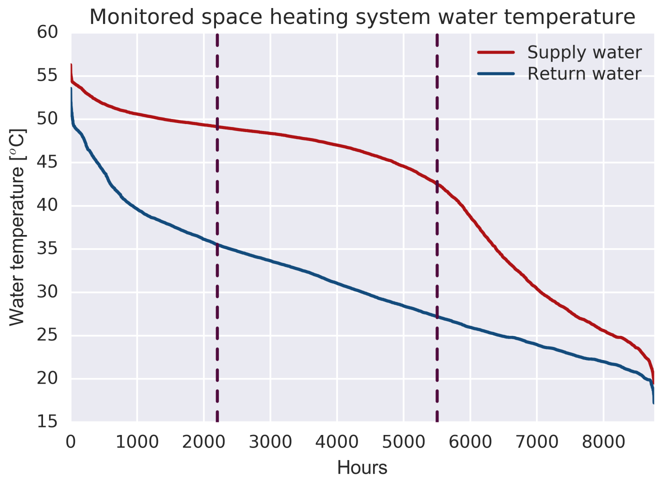

Figure 13: Load duration curve of the monitored supply and return water temperature of space-heating system.

5.1. *Load duration curve*

The district heating networks in the UK require high pumping power capacities due to low Δt across the network. It is often thought that the entire heating network is prone to this problem. However, this analysis shows that it is hydraulic imbalance problem which leads to high return water temperatures in the district heating network.

The load duration curve in Fig. 13 further elaborates that, the Δt is mostly above 20 between 2100 - 5500 hours in a year and suddenly reduces afterward. Moreover, the return water temperature remains very high for 2100 hours. This can be presumed due to the hydraulic imbalance in late spring and early autumn season. The hydraulic imbalance issue can be attributed to the incorrect installation of heating equipment or the absence of flow-limiter valves on return water pipe. This explains that space-heating systems can operate until 43^{o}C, but the return water temperature must be restricted in-between 35 - 28^{o}C for achieving high Δt throughout the year.

5.2. *Recommendations*

The hydraulic imbalance in the heating network is usually due to the incorrect estimation of the heat consumption, over-sized control valves, over-sized or incorrect adjusted pumps, problems with equipment commissioning, the absence of flow-limiter and control equipment [9]. It is recommended that following measures might improve the hydraulic imbalance issue in the UK heating networks.

1. Implementation of balancing valves and flow-limiters on return water pipes in the heating network.
2. Installation of pressure independent thermostatic radiator valves (TRVs) in high-rise buildings.
3. The district heating pipes shall not be over-sized intentionally.
4. Installation of hydronic radiators in top bottom opposite end (TBOE) configuration instead of bottom bottom opposite end (BBOE) configuration.

This study shows that, TRVs alone are unable to maintain the hydraulic balance in existing space-heating system in buildings. Moreover, importance should be given to the pipe sizes in the LTDH network. These are often over-sized for keeping flow-rate lower in the network, but this leads to higher heat-losses, head-loss, pumping power and energy consumption. The hydraulic balance in the space-heating systems might improve, if pressure independent TRVs are used on radiators. This is considered as ideal solution for space-heating systems especially in high-rise buildings. Otherwise, another solution can be using pre-setting function of TRVs on radiators, along with balancing valves and differential pressure controller in the district heating network, as discussed by Zhang et al. [10]. The pre-setting function restricts the amount of water flowing through the radiator.

Furthermore, it is believed that the Δt might increase significantly, if LTDH radiators are connected in top bottom opposite end (TBOE) configuration, instead of bottom bottom opposite end (BBOE). In the UK, hydronic radiators are commonly connected in the bottom, bottom, opposite end (BBOE) scheme according to the BS-3521 standard [36], which lays down condition for connecting radiators in the heating network. BBOE connections are used in old-fashioned heating networks, where the flow-rate and supply water temperatures are kept high [37, 38]. Even-though, the current focus is on reducing supply water temperatures and improving Δt, but hydronic radiators are still being installed in the BBOE scheme.

It is recommended that, the optimisation of heating networks, especially space-heating system loop inside buildings is required in the UK. This can be achieved by dynamic analysis of the heating network, development of weather based auto-regression model for correct heat demand prediction in extreme events [39]. If the proposed recommendations are applied in the LTDH networks, then considerable energy consumption savings are expect to be achieved. This will consequently have a positive environmental impact as well.

6. Conclusion

This paper presents a model which investigates the hydraulic performance and calculates flow-rate, heat-losses, pumping power and energy consumption of the LTDH network. This model is used to demonstrate the hydraulic performance in four operational different scenarios for a planned LTDH network in Nottingham, UK. The results are calculated using actual network parameters, monitored weather data and space-heating system operational data from an existing building. The implication of reducing supply water temperature on hydraulic performance of the LTDH network is analysed in each scenario and the optimum scenario is found. Following are the main conclusions drawn from this research.

1. The weather data shows retrofitting of building has significant impact on the energy consumption. The hourly monitored weather time-series data shows that, Nottingham receives a fairly high amount of solar radiations and the outside air temperature rarely goes below 0^{o}C. This explains the significance of solar radiations in heat demand calculations. Moreover, deep-retrofitting of existing building has great impact on the energy performance of building. The building used as case study in this shows that

deep-retrofitting has reduced the energy consumption by more than 50% and increased the operative temperature by 2^oC.

2. This study demonstrates that the conversion of existing buildings to LTDH network is technically possible, as the supply water temperatures are already lower than 60^oC. However, high return water temperature due to the hydraulic imbalance in existing boiler based space-heating systems leads to high heat-losses. This needs to be resolved before their conversion to LTDH network.
3. The hourly monitored data from the space-heating system shows that the regulation of return water temperature with respect to outside temperature is more significant, than the supply water temperature for achieving high Δt. Moreover, the Δt decreases with increase in outside temperature and the average Δt throughout the year is just 11. Even-though, the heating network has been designed and configured for the Δt of 30.
4. While comparing different operational scenarios it is found that the energy consumption of the LTDH network is lowest in scenario 3, when the flow-rate is variable and supply water temperature is kept constant from the sub-station. The variation in supply water temperature reduces the heat-losses in the LTDH network, but increases energy consumption of the LTDH network. Therefore, fluctuating renewable heat sources and low-grade waste heat will impact the hydraulic performance of the network.
5. The heat-losses in existing district heating networks which are currently operating at constant flow-rate and supply water temperature can be reduced significantly, if the supply water temperature is regulated using weather compensation control at the sub-station. Nevertheless, this will increase the pumping power and energy consumption in these networks.

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Nomenclature

ΔP_v differential pressure across the value [bar],[kg/ms^2]

Δt delta t

λ_{gs} thermal resistance of the ground surface [m^{o}C/W]

λ_g thermal conductivity of the ground surface [W/m^{o}C]

λ_i thermal conductivity of the insulation [W/m^{o}C]

μ dynamic viscosity [kg/ms]

ν kinematic viscosity [m^2/s]

ρ fluid density [kg/m^3]

θ correction factor for each pipe

C_p specific heat capacity of hot water [KJ/kg^{o}C]

d pipe diameter [m]

D_g diameter of outer soil affected by the DH pipes [m]

D_m diameter of outer insulation thickness [m]

D_o diameter of steel pipe [m]

DH district heating

e pipe roughness [m]

f friction factor

g acceleration due to gravity [m/s^2]

H effective burial depth of each pipe [m]

h_f head-loss [meters]

K_v regulation capacity of control or balancing value

l pipe length [m]

L_c distance between the supply and return pipe [m]

$LTDH$ low-temperature district heating

m mass flow-rate [kg/s]

P pressure [bar], [kg/ms^2]

Q heat load [KW]

q volume flow-rate [m^3/s]

Q_{loss} heat-loss in pipes [KW]

R_e Reynolds number

R_{gu} thermal resistance between ground-surrounding [m^{o}C/W]

R_g thermal resistance of surrounding ground [m^{o}C/W]

R_h thermal resistance at the ground surface [m^{o}C/W]

R_{ig} thermal resistance between insulation-ground [m^{o}C/W]

R_i thermal resistance of insulation material [m^{o}C/W]

R_{total} total thermal resistance [m^{o}C/W]

R_{wi} thermal resistance between water-insulation [m^{o}C/W]

S_c distance between the supply and return pipe centres [m]

S_d depth from ground to pipe centre

T_{inlet} inlet water temperature in district heating pipe [^{o}C]

T_{outlet} outlet water temperature from district heating pipe[^{o}C]

T_{out} outdoor air temperature [^{o}C]

T_r district heating return water temperature

T_s district heating supply water temperature

T_u soil temperature at 30 cm depth [^{o}C]

U heat transfer coefficient of each pipe [W/m^{2o}C]

v flow velocity [m/s]

Table 1: Main material properties of flat, before and after the deep-retrofit.

Component	Before retrofit	After retrofit
	U- value (W/m^2K)	U- value (W/m^2K)
Wall	2.1	0.3
Glazing	2.727	1.8
Roof	0.346	0.123
Floor	2.128	2.128
Overhang	2.128	2.128
Heat demand (KWh)	23,897	11,253

Table 2: Radiators installed in the flat from REOMRBAN project.

No.	Room	Radiator size	Radiator type	Power output (W)
1	Hallway	1100 x 600	Single panel, single convector	1,100
2	Lounge	1600 x 600	Double panel, double convector	2,845
3	Bathroom	500 x 600	Double panel, double convector	889
4	Kitchen	400 x 600	Double panel, double convector	711
5	Bedroom - 1	1400 x 600	Single panel, single convector	1,400
6	Bedroom - 2	1000 x 600	Single panel, single convector	1,000
7	Bedroom - 3	400 x 600	Double panel, double convector	711

Table 3: Comparison between different operational scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Flow-rate	constant	constant	variable	variable
Supply water temperature	constant	variable	constant	variable
Maximum flow-rate from plant room (m^3/hr)	5.34	5.87	5.31	11.71
Minimum flow-rate from plant room (m^3/hr)	5.34	5.87	0.82	0.05
Heat-loss from district heating pipes (MWh)	14.86	9.34	14.85	9.34
Maximum pumping power (KW)	70	92.68	68.82	734.07
Energy consumption (KWh)	964	1261	360	1189
Overall heat-losses in LTDH network (MWh)	62.25%	9.6%	47.66%	11.13%