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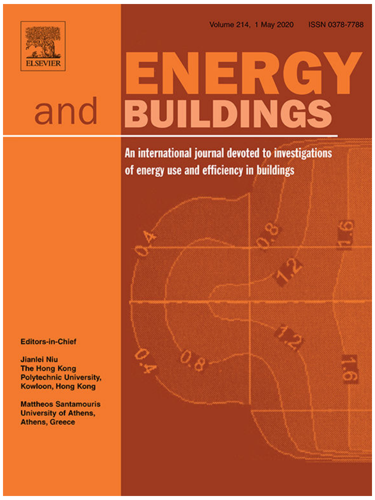

Development of A Dynamic Analytical Model for Estimating Waste Heat From Domestic Hot Water Systems

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DEVELOPMENT OF A DYNAMIC ANALYTICAL MODEL FOR ESTIMATING WASTE HEAT FROM DOMESTIC HOT WATER SYSTEMS

May 14, 2021

1 Abstract

Domestic Hot Water (DHW) production accounts on average between fourteen and thirty percent of the residential energy consumption worldwide. In UK dewllings, a quarter of the energy is consumed to produce hot water and this proportion is likely to increase as the energy required for space heating reduces over time in order to achieve demand reduction targets. As the margins for improving the performance of heating system technologies increase, the need for improving modelling accuracy and precision increases as well. Although studies have considered DHW use in buildings, there is a lack of reflection on the energy loss and performance of systems in contemporary dwellings. Current simulation tools with simplified assumptions and limited capabilities (due to a lack of considered variables and details of calculation algorithms) might lead to unreliable results in terms of the estimated heat losses.

In this research, an analytical dynamic model has been developed to estimate heat loss from a domestic hot water system based on high resolution monitored data for a set of dwellings in the UK. The model estimated heat losses during flowing and non-flowing (cooling down) conditions in the distribution system as well as heat losses from the storage tank. It was found that apart from the significant heat loss from the storage tank, short draw-offs are particularly influential in determining the amount of heat wasted. Considerable savings might be achieved ”avoiding” short draw-offs through a better control of the system and/or changes in the user behaviour. Insulating and reducing the effective length of the distribution pipe network through better design of the system similarly predict significant reductions in heat losses.

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NOMENCLATURE

Symbols

c_p	specific heat capacity	$\mathrm{Jkg^{-1}K^{-1}}$
d	diameter	mm
e	constant (Euler)	-
h	hight	m
L	length	m
l	thickness	mm
$\dot{m}$	water mass flow rate	$\mathrm{kgs^{-1}}$
M	mass	kg
r	radius	mm
R	thermal resistance	$\mathrm{m^2KW^{-1}}$
Q	thermal heat	KJ
S	surface area	$\mathrm{m^2}$
T	temperature	℃
t_1	initial time	second
t_2	final time	second
V	volume	l
U	heat transfer coefficient	$\mathrm{Wm^{-2}K^{-1}}$
UA	heat loss factor	$\mathrm{WK^{-1}}$
ρ	density	$\mathrm{kgm^{-3}}$
λ	thermal conductivity	$\mathrm{Wm^{-1}K^{-1}}$
π	constant (pi)	-
ΔT	temperature difference	K

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Subscripts

a	ambient
co	copper
f	flowing
fo	foam
$hwin$	hot water inlet
$hwout$	hot water outlet
ld	loss distribution
lf	loss flowing
lm	log mean
ls	loss storage
lzf	loss zero flowing
lt	loss total
i	isolation
p	pipe
p_{in}	pipe inside
sp	supplied
t	tank
tco	tank copper
tfo	tank foam
t_{out}	tank outside
w	water
w_{in}	water inlet
w_{out}	water outlet
ws	water supplied
zf	zero flowing

---

2 Introduction

Reduction of energy consumption and green-house gas emissions are key challenges for the coming decades. The UK Government has committed itself to reduce CO_2 emissions by 80% in 2050 relative to the 1990 levels with the objective towards zero emission from the domestic sector [1]. Recent studies [2] have shown that reductions in energy consumption by 50% or more are likely to be needed if carbon reduction targets are to be met. Studies have shown that the residential sector in the UK accounts for 32% of the total energy consumption [3] and about 29% of all end use related CO_2 emissions [4]. It has been estimated that hot water production accounts for about 26% of the

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total energy consumed in residential homes[5] and about 5.5% of UK's total CO_2 emissions [6]. Natural ventilation can have an affect on cooling in buildings [7] and consequently might increase the heat loss from hot water systems, whilst thermal insulation can improve energy efficiency retrofitting [8] and consequently can reduce heat losses from hot water systems. Retrofitting homes with an improved water efficiency has been considered an essential and cost-effective pathway to reduce carbon emissions and fuel expenditures in homes [9]. In the past, most of the energy consumption in the domestic sector has been dominated by space heating. However, this domination has decreased in present days as the building regulations have resulted in the reduction of energy consumption for space heating via increased insulation; the decrease of infiltration and ventilation flow rates; as well as the increase of airtightness levels in buildings [7]. In this context, it is expected that the gap of energy demand between space heating and hot water production will be even less in the future, hence research to reduce energy consumption for hot water production will become more relevant and important.

Depending on the cold water inlet temperature, the technology and efficiency of the system used to produce hot water, and its energy consumption can range between 14% to 30% of the residential energy consumption [10]. Domestic hot water in UK dwellings is mostly produced from regular and combi-boiler systems. A combi-boiler delivers hot water and heating on demand and does not need to be fitted alongside any storage cylinder avoiding space requirements, storage heat losses and time to heat up the storage water. Combi-boilers due to their compatibility can be installed in kitchens shorting the pipe run between boiler and kitchen tap. In addition, they are able to ensure high water pressure as the water drawn from taps and shower comes through at mains pressure. Regular boiler systems come in three parts: a boiler, a hot water cylinder and at least one water storage tank located in the loft. These systems are great for large dwellings where a lot of hot water is used at the same time. The setup of a regular boiler requires loft space and an airing cupboard to house the tanks and hot water cylinder where due to the storage requirements the heat loss could be significant higher compared to a combi-boiler system. For combi-boilers, the hot water outlet temperature is recommended at 60 ℃ although it is commonly set lower than this. This depends on the mixing or tempering valves installed at the outlet taps to mix and deliver hot water at temperature between 35-40 ℃ comfortable for human body skin. For regular boilers, the domestic hot water cylinder thermostat should be set at 60-65 ℃ to kill off harmful bacteria such as Legionella. For health and safety reasons, such as legionella control, hot water must be stored at a minimum temperature of 60 ℃ for at least one hour a day [11] and it should have a minimum distribution temperature of 50 ℃ [12]. If the thermostat is set higher, the water that comes out of the taps will be too hot and there will be a risk of scalding. Despite this suggested supply temperature from regulations, based on measurement results [13] it was found that the average delivery temperature for regular boilers was around 53℃ (± 1.5 ℃), whilst for combi-boilers the average temperature was around 49℃ (± 2 ℃). Another study using measured data showed that in the case of combi-boilers, the highest percentage of the hot water volumes used are drawn at temperatures between 45 to 51 ℃, whilst considerable draw-offs occur below 45 ℃ [14]. Combi-boilers produce hot water only when needed (i.e. where there is a draw-off) and this type of control can lead to substantial energy savings, whilst with a regular boiler, hot water tends to be produced twice a day (morning and evening time-periods), regardless if it gets used or not and is stored inside the cylinder. Once the temperature of the stored water drops below the cut-off temperature due to drawn-offs or heat loss from the storage cylinder to the environment, the sensors located inside the hot water cylinder send a signal to the boiler to reheat the stored water to the design set-point temperature. Whereas boilers create hot water using gas, immersion heaters installed inside a hot water storage cylinder use electricity and are relatively easy to install and operate. The main advantage of having immersion heaters is that these are separate from the boiler, meaning if a boiler breaks down hot water can still be generated. Another advantage of immersion heaters is that if the hot water cylinder is well insulated, water will remain hot for several hours, even after the immersion heater has switched off. A disadvantage is that when the tank has been drained off hot water, there is no other option but to wait for it to fill up with water and heat up again. However, the biggest disadvantage is cost: electricity is relatively more expensive compared to natural gas. Pratt et.al [15] estimated that the average standby load of electric hot water tanks was about 1200 kWh/yr accounting for 24% of the total energy consumption for hot water production. Armstrong et.al [16] found that de-stratifying a system to sterilise the bacteria led to a 19% reduction in the effective hot water storage capability. Increasing the tank size to compensate the loss would lead to an 11% increase in the energy consumed due to standing heat losses. Standing heat losses for storage water heaters was estimated to be up to 24% for a 150 litre and 19% for a 200 litre storage capacity, respectively [17]. Based on gathered utility data [18] it was found that gas consumption decreased by about 33% after a post-retrofit process that replaced the tank type water heaters with tank-less water heaters. In the UK the most significant attempt to tackle the standing losses associated with storage hot water cylinder has been the move to replace regular boilers with combi-boilers to provide instantaneous supply. Although older boilers can have a heat generation efficiency of up to 81%, the actual delivered heat efficiency can drop up to 38%, or even lower depending on the draw-off characteristics [19]. As of 2010, 45% of homes in the UK have a combination boiler [20]. The hot water consumption patterns influence directly the amount of hot water volume and the energy consumption. Studies [21, 22, 23, 24] have shown that potential reductions can be achieved by a combination of behavioural changes and the use of more energy efficiently technologies. The duration of short draw-offs such as tap events is very uncertain and is quoted as yielding a 40 second average duration[25]. Another study points out that 70% of the tap durations were less than 20 seconds long [26]. Factors such as plumbing layout, pipe sizing and pipe location, quantity of hot water use and patterns, leakage, as well as insulation levels of pipework have been demonstrated to be significant in determining the effectiveness of the delivered heat and hot water [27]. Data collected during a pilot field study indicated that about 30% of water and 40% of energy are wasted while waiting for hot water to be delivered to the point of end use[28]. Based on high resolution measured data it was found that at least 20% of all hot water is consumed through very short draw-offs and this has implications for waste heat as the water will cool down whilst transported via the pipe from the boiler to the tap[29]. About 25-50 litres per day on average is wasted either while waiting for hot water or it is not used after it has cooled off accounting approximately 20% of the total hot water use being wasted [30]. Distribution losses for residential buildings with non-recirculating distribution systems may range from 10-40% of the annual

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energy consumption for hot water production [31]. The insulation of the pipe network has a significant impact on the energy savings, particularly in homes with unconditioned spaces. In some cases up to 30% of the savings could be achieved by insulating the entire distribution system [32]. According to a study [33] that was based on energy models using optimization of hot water system design and pipe insulation, significant reduction of emissions, heat loss and hot water consumption could be achieved. It was estimated that about 5-6% of hot water service is lost in the pipe network as short draw-offs can not reach the pipe outlet, whilst heat loss from storage tanks ranges from 5-17% of the total supplied heat into the hot water storage tank [34]. An experimental investigation [35] monitored the temperature drop gradient for a pipe length of two metres long and found that the water temperature drop followed a linear function for the first thirty minutes and then remained close to the ambient temperature. [36] found that heat loss from hot water pipe distribution to the surrounding ambient, significantly affected water and energy waste under low flow rates for long lengths of uninsulated pipes, whilst insulation could reduce 7-13% of the heat losses. A system consisting of multiple point of use could achieve up to 28-50% savings compared to a storage tank heater with tree-type distribution piping [37]. The hybrid solution of a centrally located storage water heater combined with multiple small capacity water heaters has the potential to deliver hot water more quickly and efficiently than a tank-only system [38]. For a typical domestic hot water system the waiting time for hot water (at 40 ℃) at the point of use was typically up to thirty seconds, however a shorter waiting time was identified for continuous recirculated and parallel pipe systems [39]. For a typical dwelling with an average pipe network length ranging between 4-10 meter, the efficiency of the domestic hot water system was estimated to around 0.30-0.77 and the heat heat loss to 23-70%[40]. If a 15 mm pipe is supplying a hot water tap and there is a 10 m dead leg, then 1.5 litres of water will have to be drained first until water at the desired temperature is obtained. If the tap is used 20 times a day, during a year times 7.5 m^3 of hot water will be wasted costing about £30 and £60 respectively for gas and electricity systems [41].

Despite the above research, there are still some open questions, for example, understanding: the heat loss for typical tank and comb-boiler systems, the position of the boiler/tank in relation to the draw off points, the effect of the (almost universal) lack of pipework insulation and the effect of the draw-off characteristics associated with specific users. All these factors vary from home to home and it is unclear how current modelling and performance tools treat waste heat from DHW systems when compared to installations and measured data in real homes.

A part from measured data, there are also models that can estimate heat losses from DHW systems. Using state-of-the art simulation tools, it was found that the results using different tools can vary between -30 to +45% when estimating heat loss from a domestic hot water system [42]. These discrepancies can be attributed to the underlying methodology used in most current existing models for estimating heat losses that are based on simplified steady-state calculation methods and assumptions. Dynamic models on the other hand did not calculate the heat losses in the distribution system after the draw-offs took place, and consequently did not estimate the heat losses during the cool-down period [42]. Also, dynamic models carry out simulations down to a minutely therefore not considering and estimating heat losses for draw-offs with a duration of less than one minute long. In this research, a dynamic

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simulation model has been developed to overcome the above gaps. The model estimates heat losses in a distribution system during and after draw-offs (cool-down time period). The model can estimate heat loss from draw-offs down to secondly time-step using real measured water flow rates and supply temperatures making it possible to investigate the impact of short draw-offs on heat losses. Also, a well mixed tank model for estimating heat loss from hot water storage cylinder has been developed. This paper examines the heat loss from domestic hot water pipe networks with a developed dynamic simulation model for a set of typical UK homes which then estimates potential heat loss reductions in comparison to existing literature. The work is based on high resolution measured data. It examines in detail the heat losses for two typical hot water systems i.e., a regular boiler with storage cylinder and a combi-boiler system, whilst the heat losses caused in the distribution system from short draw-off's are estimated for all considered homes. The results estimate potential waste heat reductions that can be achieved through behavioural changes avoiding especially short draw-off's, insulating or reducing the hot water distribution pipework, and replacing the traditional regular boiler tanked system with a combi-boiler avoiding the need for hot water storage. The effect of short draw-offs on heat losses is highlighted emphasising that more sophisticated controls and changes should be consider to minimise heat loss. The developed dynamic model can be adapted and incorporated with existing simulation tools and can therefore contribute to improving accuracy of estimating heat losses especially during non-flowing (cool-down) conditions.

3 Methodology

The calculation of thermal losses from a domestic hot water pipe network is explained in BSEN 15316-3-2[43] in detail, however these calculations are based only on static parameters such as pipe length, number of tapping per day, distribution efficiencies and constant inlet/outlet temperatures. Normally, heat losses are estimated from the above standard and the calculation considers the nominal hot water temperature in the pipe flowing during that certain draw-off. The developed model in this research however overcomes this issue as it considers the real flowing temperature during each draw-off and not the nominal temperature so the estimation should be more accurate. A model developed in EnergyPlus [44] estimates the pipe heat transfer by discretizing the pipe length into a number of twenty nodes. However, from model description and simulation output results it was found that the model only estimated the heat loss during flow conditions. Hence, the model may actually be underestimating losses since the analytical model revealed that most of the heat losses occur under zero-flow conditions. In order to have more precise and reliable results on estimating heat loss of the DHW system network, an analytical dynamic model is developed based on ASHRAE [45] that uses the Log Mean Temperature Difference (LMTD) method and heat loss factors derived from experimental work by [46, 47] described in the following sections. The model estimates heat loss from the distribution pipe under flow and zero flow (cooling down) conditions. In the present work, the model is used to explore further the impact that draw-off frequency characteristics from the distribution system may have on heat loss. Figure 1 shows the developed methodology in this research where measured data are incorporated into an analytical model and simulated to obtain the results. The analytical model was created using Matlab. The model incorporates the measured data for a typical day (cases 1 and 2) and for an entire year

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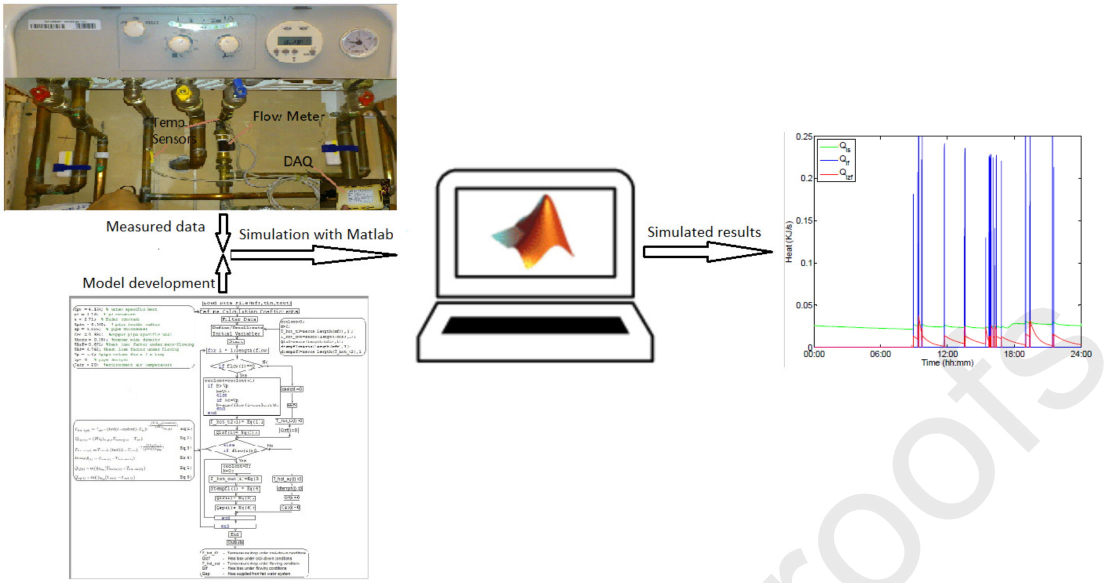

Figure 1: Research methodology overview, incorporating measured data into an analytical Matlab model to obtain simulation results

(case 3).

3.1 Heat supplied to hot water

The surface temperature of the copper pipes at these inlets and outlets points was used to indicate the water temperature and hence to estimate the supplied heat using,

$$Q_{sp} = \dot{m}_w c_{pw} \left(T_{w_{in}} - T_{w_{out}}\right). \tag{1}$$

3.2 DHW tank heat loss

The estimation of heat loss from a hot water storage cylinder can be a complex task and for more accurate results the calculation should consider the natural logarithm of the ratio between outer and inner diameter and convective heat transfer coefficient resistance. Convective heat transfer from the cylinder to the surrounding ambient can be influenced by the water temperature inside the cylinder which can be a function of the stratified layers of water temperature inside the storage cylinder where the heat losses vary from one layer to another as well as the ambient temperature. Models and methods have been developed [48, 49, 50] to consider the complexity of heat transfer and estimate heat loss from hot water storage cylinders. Another phenomenon that influences storage tank thermal behaviour and consequently heat losses is the "stacking" effect. Stacking occurs when hotter water located at the top of the water heater tank becomes stacked on top of colder water at the bottom of the tank. In order to model the stacking effect on the heat losses from the storage tank, the water temperature inside the tank for each stratified layer and the temperature change rates have to be measured. In this study, the heat loss calculation from hot water storage cylinder is simplified since the water temperature inside the hot water cylinder has not been measured and monitored. An approximated well-mixed storage tank temperature (T_{ws}) has been considered that is used in the

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calculation. The water temperature is measured at the outlet pipe from the water storage cylinder. An average constant ambient temperature of 20 °C is considered in the calculations.

For the case when water that is stored in the tank is held at a constant temperature T_{ws} and the ambient air temperature is T_a, the heat loss (Q_{st}) in the time interval ($t_2 - t_1$) is,

$$Q_{ls} = U_t S_t \left(T_{ws} - T_a\right)\left(t_2 - t_1\right), \tag{2}$$

where,

$$U_t = \frac{1}{R_{co} + R_{fo}} = \frac{1}{\frac{l_{tco}}{\lambda_{co}} + \frac{l_{tfo}}{\lambda_{fo}}}, \tag{3}$$

and,

$$S_t = 2\pi r_{t_{out}} h_t + 2\pi r_{t_{out}}^2. \tag{4}$$

When stored water is heated up periodically to a temperature T_{ws}, the heat loss for the time interval is given by,

$$Q_{ls} = U_t S_t \left(T_{ws} - T_a\right) \frac{\left(1 - e^{-\alpha(t_2 - t_1)}\right)}{\alpha} \tag{5}$$

where, $\alpha = \frac{U_t S_t}{\dot{m} c_{p_w}}$. Equations (2-5) assume that the fluid in the tank is well mixed. Equation (2) estimates the heat loss from the storage cylinder when the water in the tank is held at a constant temperature. It considers the heat transfer coefficient that is a function of thermal resistances from cylinder material and insulation material estimated in equation (3). It considers the cylinder heat loss surface area estimated in equation (4) as well as the temperature of water stored in the cylinder and the surrounding ambient temperature. Equation (5) estimates the heat loss when the stored water in the cylinder is heated up periodically to a temperature where in addition to equation (2) the water mass flow rates that flow through the tank are taken into consideration. This is incorporated into the calculations through a natural logarithm exponential. The estimated heat loss from the storage cylinder are expected to be more accurate in this research by incorporating the measured water mass flow rate and the outlet temperature from the tank (the considered fluid in the tank is well mixed) into the equation (5) .

3.3 Pipe network heat loss

When hot water flows from the boiler or the tank to a draw-off point, the heat loss in the pipe network is considered to occur predominantly through convection and radiation under two conditions: during fluid flow; and when the fluid is static, i.e. cooling down, hence heat loss through conduction is neglected in this study. During flow conditions, the heat loss is given by,

$$Q_{lf} = \dot{m} c_{p_w} (T_{hw\,in} - T_{hw\,out}), \tag{6}$$

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and,

$$Q_{lf} = UA_f(\Delta T_{lm}), \tag{7}$$

where (for water flowing in pipes in a constant ambient temperature),

$$\Delta T_{lm} = \frac{[(T_{hw\,in} - T_a) - (T_{hw\,out} - T_a)]}{ln[(T_{hw\,in} - T_a)/(T_{hw\,out} - T_a)]}, \tag{8}$$

and,

$$T_{hw\,out} = T_a + [T_{hw\,in} - T_a]e^{-\left(\frac{UA_f L_p}{\dot{m}c_{pw}}\right)}. \tag{9}$$

Equations (6) and (7) determine the heat lost from the pipe network during flow conditions. Equation (8) estimates the LMTD under flow conditions. Equation (9) estimates the water temperature leaving the pipe, derived from Equations (6, 7 and 8). Heat loss under zero-flow conditions is given by:

$$Q_{lzf} = (Mc_p)_{w,p,i}(T_{hw\,t_1} - T_{hw\,t_2})/(t_2 - t_1), \tag{10}$$

where

$$M = \Sigma\dot{m}_w \leq V_p, \tag{11}$$

$$V_p = \pi r_{p_{in}}^2 L_p, \tag{12}$$

and,

$$Q_{lzf} = UA_{z_f}(\Delta T_{lm}). \tag{13}$$

For water standing in pipes in a constant ambient temperature,

$$\Delta T_{lm} = \frac{[(T_{hw\,t_1} - T_a) - ((T_{hw\,t_2} - T_a)]}{ln[(T_{hw\,t_1} - T_a)/(T_{hw\,t_2} - T_a)]}, \tag{14}$$

and,

$$T_{hw\,t_2} = T_a + [T_{hw\,t_1} - T_a]e^{-\left(\frac{UA_{zf}(t_2 - t_1)}{Mc_{p_{w,p,i}}}\right)}. \tag{15}$$

Equations (10) and (13) represent the upper limits (maximum) of heat loss. They are only valid if the standing water in the pipe is cooled off ($T_{hw\,t_2} = T_a$). It should be noted that heat loss and temperature drop are not constant along the length of the pipe distribution network. This is because the temperature of each successive pipe length is lower than the temperature before the previous pipe length section. This applies to both flow and zero-flow conditions. The pipe temperature decays exponentially, hence the use of the LMTD method.

Equation (11) estimates the mass M (kg) of water 'stored' in the pipe and will be subject to cooling during zero flow conditions. M is the sum of mass flow rate $\dot{m}$ (kg/s) during the flowing period (seconds). If M is higher than the maximum volume V (l) of the branch pipe length, then M is equal to V (l) otherwise M is the sum of $\dot{m}$. Here the density of water is assumed to be 1000 kg/m^3.

The water temperature in the pipe at anytime during periods of cooling is determined by Equation (15), derived from Equations (10, 13 and 14). The total heat loss from the pipe network during zero flow is determined by calculating the pipe temperature at time (t_2) and multiplying the average heat loss rate between (t_1) and (t_2) determined by Equation (10) multiplied by the cooling period $(t_2 - t_1)$. In this case the time interval for the calculation was the same as the resolution of the data at secondly time-step. The parameters that were measured and used in the calculation model are the water temperature entering the pipe $(T_{hot_{in}})$, the room air temperature (T_{air}) and the water flow rate $(\dot{m})$. The calculation assumes that the air temperature is constant although an average ambient air temperature was estimated from the monitoring data in order to model the conditions in the home more precisely.

The total heat loss in the DHW distribution network for a house with combination boiler system is estimated by, $Q_{lt} = Q_{lf} + Q_{lzf}$ and by $Q_{lt} = Q_{lf} + Q_{lzf} + Q_{ls}$, for a house with the tank system.

Figure 2 shows the algorithm diagram that estimated the pipe network heat losses. It uses data of water flow and inlet/outlet temperatures measured at secondly timestep, constant coefficients, pipe length and radius. With the equation described from the 6 to 15 it estimates the temperature and consequently heat loss from the pipe network during flow and non-flow conditions. Note that the labelled equations in the diagram do not necessarily match/represent the labelled equations in the paper. These labelled equations in the diagram are shown as they take place in the flowing calculation algorithm. Appendix A shows the process of loading, filtering and the calculation algorithm loop that is used to estimate the heat loss from the hot water pipe distribution network during flow and zero-flow (cooling-down) conditions.

3.4 Considered homes for analysis

In this study, 15 homes were monitored in significant detail. All participating homes are mid-sized, owner-occupied family homes in the midlands UK. They were monitored as part of a 4 year investigation into demand reduction in the home[1]. The homes are typical of their respective years of construction (1900 to 2002) and of those found throughout the UK. All homes are occupied by families that range in number and age, from 2 persons to 6 persons and range from parents with babies, children, adult and relatives living together. The childrens' and teenagers' age varies from 3 to 21 years old while the adults age varies from 24 to 56 years old.

Table 1 presents the considered homes for analysis and shows occupancies, types of hot water system (regular

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[1] 'LEEDR: Low Effort Energy Demand Reduction', (EP/I000267/1), www.leedr-project.co.uk

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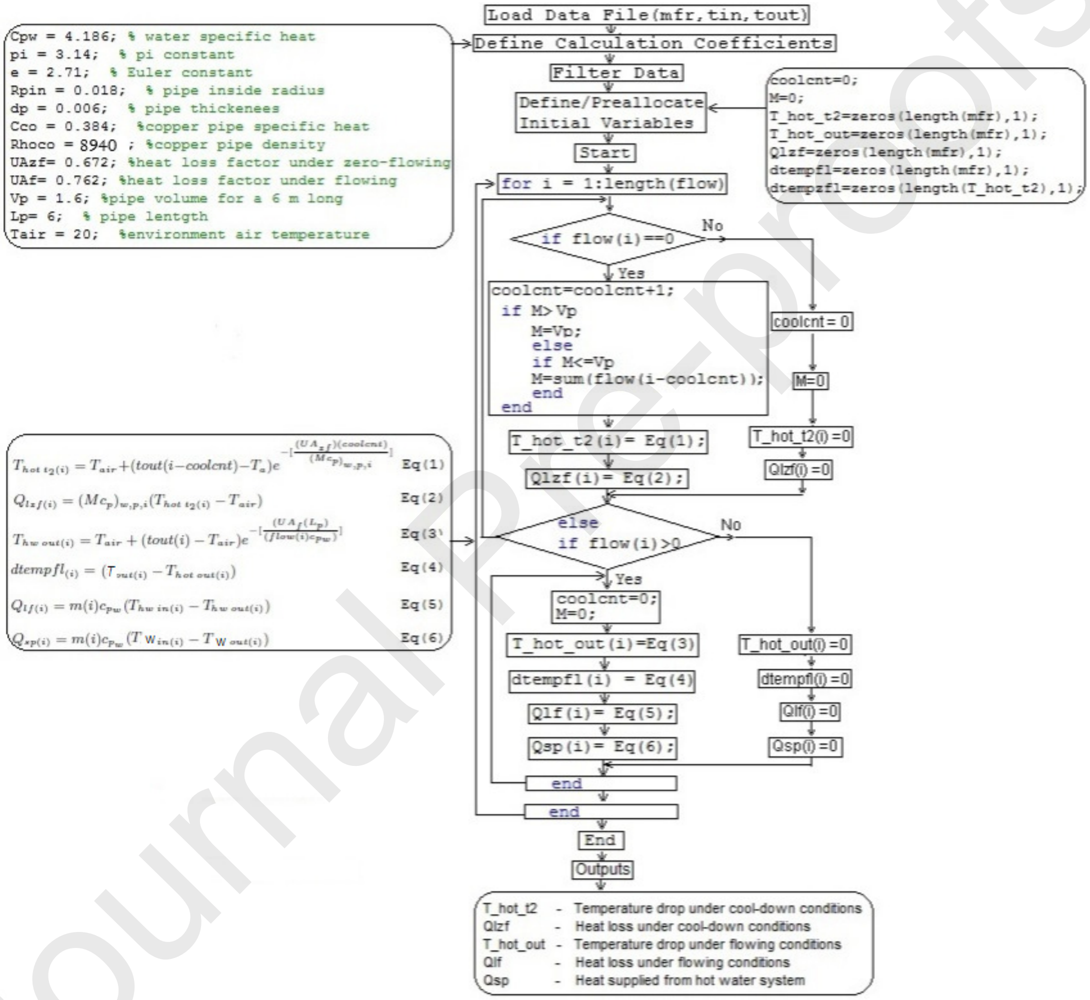

```
Cpw = 4.186; % water specific heat
pi = 3.14;  % pi constant
e = 2.71;  % Euler constant
Rpin = 0.018;  % pipe inside radius
dp = 0.006;  % pipe thickenees
Cco = 0.384;  %copper pipe specific heat
Rhoco = 8940 ; %copper pipe density
UAzf= 0.672; %heat loss factor under zero-flowing
UAf= 0.762; %heat loss factor under flowing
Vp = 1.6; %pipe volume for a 6 m long
Lp= 6;  % pipe lentgth
Tair = 20;  %environment air temperature
```

```
coolcnt=0;
M=0;
T_hot_t2=zeros(length(mfr),1);
T_hot_out=zeros(length(mfr),1);
Qlzf=zeros(length(mfr),1);
dtempfl=zeros(length(mfr),1);
dtempzfl=zeros(length(T_hot_t2),1);
```

```
coolcnt=coolcnt+1;
 if M> Vp
    M=Vp;
    else
    if M<=Vp
    M=sum(flow(i-coolcnt));
    end
 end
```

```
coolcnt=0;
M=0;
```

$$T_{hot\ t_2(i)} = T_{air} + (tout(i - coolcnt) - T_a)e^{-[\frac{(UA_{zf})(coolcnt)}{(Mc_p)_{w,p,i}}]} \quad \text{Eq(1)}$$

$$Q_{lzf(i)} = (Mc_p)_{w,p,i}(T_{hot\ t_2(i)} - T_{air}) \quad \text{Eq(2)}$$

$$T_{hw\ out(i)} = T_{air} + (tout(i) - T_{air})e^{-[\frac{(UA_f(L_p)}{(flow(i)c_{pw})}]} \quad \text{Eq(3)}$$

$$dtempfl_{(i)} = (T_{out(i)} - T_{hot\ out(i)}) \quad \text{Eq(4)}$$

$$Q_{lf(i)} = m(i)c_{pw}(T_{hw\ in(i)} - T_{hw\ out(i)}) \quad \text{Eq(5)}$$

$$Q_{sp(i)} = m(i)c_{p_w}(T\,\mathrm{W}_{in(i)} - T\,\mathrm{W}_{out(i)}) \quad \text{Eq(6)}$$

T_hot_t2 - Temperature drop under cool-down conditions
Qlzf - Heat loss under cool-down conditions
T_hot_out - Temperature drop under flowing conditions
Qlf - Heat loss under flowing conditions
Qsp - Heat supplied from hot water system

Figure 2: Algorithm layout for heat loss analytic calculation model

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Table 1: The occupancies and hot water generation systems in fifteen surveyed homes.

House	Occup.	Adu./Chil.	Child(s)(ag)	HWS	Shower type	Cap.(kW)	Dishwasher
H08	4	2/2	11/14	Tank	2 Elec.	7.5,10.8	Dishwasher
H09	4	2/2	9/12	Combi	1 Elec.,1 HWS	9.28	Dishwasher
H10	4	2/2	4/6	Combi	2 HWS	28	Dishwasher
H11	4	2/2	6/12	Combi	1 Elec.	9.8	Manually
H23	4	2/2	3/6	Tank	1 Elec.	8.5	Dishwasher
H28	4	2/2	16/18	Tank	1 Elec.	9.8	Manually
H30	2	1/1	12	Combi	1 HWS	35	Dishwasher
H33	4	2/2	7/9	Combi	1 Elec.,1 HWS	9.5,28	Dishwasher
H37	4	2/2	8/11	Combi	1 HWS	37	Dishwasher
H39	4	2/2	9/13	Combi	1 Elec.	9.5	Dishwasher
H40	4	2/2	8/3	Tank	2 HWS	-	Dishwasher
H41	6	3/3	12/17/21	Tank	2 Elec.	9.5,10.8	Dishwasher
H42	4	2/2	5/7	Combi	2 HWS	28	Dishwasher
H43	4	2/2	12/14	Combi	1 Elec.,1 HWS	9.5	Dishwasher
H45	3	2/1	13	Combi	2 Elec.	8.5,9.5	Dishwasher

system with storage tank or combi-boiler) used to produce domestic hot water, shower types (electric or hot water system) and dishwashers installed in the homes. The shower types and capacities are noted, where the capacity of a combi-boiler supplied shower will be the maximum boiler and electric shower devices output. In this analysis, only the hot water that has been supplied from a boiler or a storage tank was measured however not the hot water supplied from power showers. DHW flow rates and water flow temperature output from the boiler or storage tank were sampled every second over the duration of a year alongside ambient temperatures in the homes. Note that the house numbers refer to the original project code labelling and have no further meaning.

In many of the considered homes the heating and domestic hot water system was refurbished in recent years. In nine of the fifteen homes there are combi-boilers that provide heating and instantaneous hot water. While for the other six homes hot water is provided from regular boilers with storage tanks. About seven homes have only electric showers installed, while five have showers integrated with the hot water system, three homes have both electric and hot water system showers. The number of end use categories varies, each home has at least: 2 to 4 taps for hand wash, a tap for the kitchen sink and one point of use for bath tubs and showers. The length of the pipe network also varies from home to home. The approximate network length ranges from 5 to 20 meters, depending on location of the point of use and its complex ”tree” structures. None of the homes has insulated the distribution pipe network. All values of the relevant parameters used in the calculation algorithm will be explained in the following section.

3.5 Modelling assumptions

Modelling the real distribution pipe network system for each of the fifteen homes is repetitive and time consuming. In order to reduce the workload but at the same time get the desired outputs (subject to the objective of this study), three modelling cases are considered:

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3.5.1 Case 1

Two typical homes labelled H37 and H41 are simulated where hot water is produced via a combi-boiler (H37) and a storage tank equipped with immersion heaters (H41), respectively.

H37 is a detached house built in the 1970's. Double glazing and additional insulation has been installed. Two adults and two teenage children (8-13) live in here. The heating system was upgraded in 2008 when the old tanked system and boiler was removed and replaced with a combination boiler. Further renovation included an en-suite bathroom in the master bedroom which was fitted with a shower fed from the combination boiler. The original bathroom was and remains fitted with an electric shower.

H41 is a semi-detached house built in the 1960s. It was extended with a conservatory and recently double glazing and additional insulation was fitted in. Mother, Father, two adult children and two teenage children (11 and 16) live there. The house has a central heating system that is about 20 years old and DHW is provided via an open vent storage tank. There is a main bathroom and an en-suite, both of which have electric showers. Both houses are representative for the midlands UK and highlight the variation in system configuration that is common in UK homes. H37 is very close to the national average energy consumption for this type of home (20MWh/year), whereas H41 is about 50% higher than the national average.

The heat supplied and the heat loss for these two homes has been estimated based on a typical day. The hot water use was 130 l/day and 66 l/day for H37 and H41, respectively. For both homes the real distribution pipe network with real length and pipe diameter was modelled. The heat losses from the pipe network are disaggregated for typical hot water draw-offs such as taps, sink, shower during flow and non-flow conditions. Due to the complexity of disaggregating the hot water use for each appliance, the simulations are carried out only for a typical day. The simulation model shown in Figure 2 is used to estimate the heat loss. As the model itself does not disaggregate the hot water use, the disaggregation process (as from the assumptions below) has been done separately from the mode. The heat loss is estimated for each section of pipe length where the hot water flow takes place with respective flow rates and flowing temperature. The hot water volume flow rate was measured at the outlet of the boiler/tank and hence disaggregation to the outlet level was based on the frequency and duration of the draw-offs, determined by applying the following logic based criterion to the draw-off duration:

```
$IF$ $\leq$15s, flow occurs at a tap
$ELSEIF$ $\geq$15s $AND$ $\leq$200s, flow occurs at a sink
$ELSE$ flow occurs at shower (or bath)
```

Inspection of the data was used to validate this logic and it was found to generate plausible classifications. The average indoor air temperature was used to estimate the heat transfer from the pipe network into the space. The temperature surrounding the pipe network and the storage tank was considered constant at 20°C, stratification was neglected.

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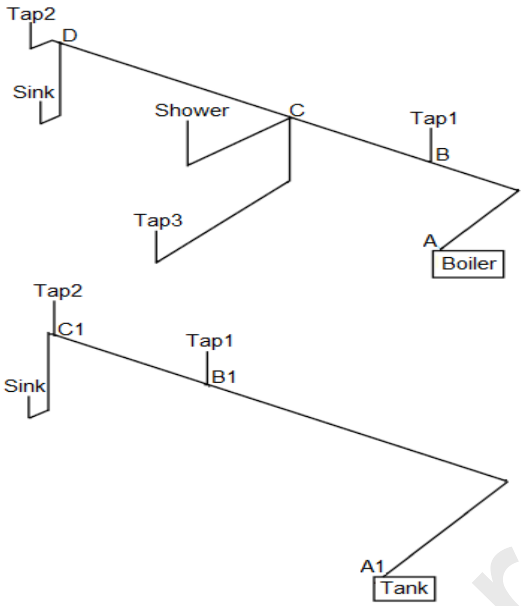

Figure 3: Hot water distribution network for H37 (top) and H41 (bottom).

The pipe networks in H37 and H41, depicted in Figure 3, differ in terms of the geometrical layout and draw-off points. H37 has five draw-offs including a sink tap (ground floor), two taps and a shower in the bathroom (first floor) and one tap in the toilet (ground floor). H41 has two taps in the bathroom (first floor) and one sink tap (ground floor). The references in Figure 3 relate to the details given in Table 2. Table 3 presents the thermal properties of water, pipe material and insulation and Table 4 details the heat loss factors for typical pipe diameters under flow and zero-flow conditions with different insulation thicknesses.

The heat loss rate from the water inside the pipe to the surrounding ambient depends on the water flowing regime. Normally, when water is under flowing condition, due to the higher conduction heat transfer, the heat losses are expected to be higher compared to under zero-flowing (cooldown) conditions as the conduction heat transfer rate is lower when water is at steady-state and not moving in the distribution pipeline. This difference or change on the rate of heat loss for two water flowing regimens in distribution pipelines is represented by two factors UA_f and UA_{zf} (as presented in Table 4). The UA_f is used to determine heat loss rates from piping during conditions when water is flowing in the pipeline, whilst the UA_{zf} is a heat loss factor used to estimate the heat loss under zero-flow (cooldown) conditions per meter of pipe length.

3.5.2 Case 2

The second case considers H37 and H41 (as in case 1), however, investigates the impact of interventions that could take place in the distribution network such as adding pipe insulation and/or shortening the pipe length. Based on the standard [51], a thickness of 13 mm insulation is assumed for the pipe with an outside diameter of less than 19 mm to limit the maximum permissible heat losses. The reduction of the effective length was estimated one meter on the main branch where every single draw should pass through. In practice this could happen by moving the

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Table 2: Geometrical parameters for distribution systems and tank unit

H37 (Combi) distribution system parameters					
Leg	L (m)	d (mm)	l (mm)	r[a] (mm)	V(l)
A-B	2.1	19	0.8	9.1	0.54
B-C	1.2	19	0.8	9.1	0.31
C-D	2.2	19	0.8	9.1	0.57
B-Tap1	1	13	0.6	6.2	0.12
C-Shower	2.5	13	0.6	6.2	0.30
C-Tap3	7	13	0.6	6.2	0.84
D-Tap2	1.5	13	0.6	6.2	0.18
D-Sink	2	13	0.6	6.2	0.52
H41 (Tank) distribution system parameters					
Leg	L (m)	d (mm)	l (mm)	r* (mm)	V(l)
A1-B1	7	19	0.8	9.1	1.82
B1-C1	2	19	0.8	9.1	0.52
B1-Tap1	1	13	0.6	6.2	0.12
C1-Tap2	1	13	0.6	6.2	0.12
C1-Sink	2	13	0.6	6.2	0.24
Tank unit parameters					
h (m)	d (mm)	l[b] (mm)	l[c] (mm)	r[d] (mm)	V(l)
0.895	445	2	17	222.5	120

[a] inside radius; [b] copper; [c] foam; [d] outside radius

Table 3: Thermal property values for water, copper and foam insulation.

Parameter	**Value**	**Unit**
Water specific heat (c_{pw})	4186	$\mathrm{Jkg^{-1}K^{-1}}$
Copper specific heat (c_{co})	384	$\mathrm{Jkg^{-1}K^{-1}}$
Copper density (ρ_{co})	8940	$\mathrm{kgm^{-3}}$
Copper thermal conductivity (λ_{co})	400	$\mathrm{Wm^{-1}K^{-1}}$
Foam specific heat (c_{fo})	1.47	$\mathrm{Jkg^{-1}K^{-1}}$
Foam thermal conductivity (λ_{fo})	0.031	$\mathrm{Wm^{-1}K^{-1}}$

Table 4: Copper piping heat loss factors

Diameter	**Insulation**	UA_{zf}	UA_f
(mm)	(mm)	($\mathrm{Wm^{-1}K^{-1}}$)	($\mathrm{Wm^{-1}K^{-1}}$)
13	0	0.391	0.623
	13	0.222	0.346
19	0	0.672	0.762
	13	0.260	0.433

Source Hiller (2006)

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boiler closer to the nearest point of use for example to the kitchen sink. Similar to case 1, the simulation has been carried out for the same typical day using the same model and implementing the above considered interventions. Model parameters (where applicable) are identical to the implementation of case 1.

3.5.3 Case 3

The third case considers all fifteen homes with a simulation run time of a whole year. The aim is to estimate the impact that very short hot water draw-offs used from taps or kitchen sinks have on the heat loss. The duration of the short draw-offs is considered ten seconds long for typical hot water draw-offs from taps such as for example from hand washing. However, literature [25, 26] points out that the duration of draw-offs is uncertain and might be slightly longer. In order to estimate the impact of the short draw-offs on the heat loss, the simulation model was run twice for each home: once with full draw-off patterns as from measurements and once with patterns where draw-offs of less than or equal to ten seconds are removed (cut-off) from the real measured water flow. The situations where short draw-offs of hot water used from the taps can be avoided might be achieved either by: (1) he change of occupant behaviour using cold water to wash hands (although this can cause a lack of hygiene and comfort); or (2) when an intelligent control system (based on the length of draw) prevents the hot water to be drawn from the boiler or storage tank and installed power heaters provide hot water at the point of use. This will prevent operation of the boiler or heater elements in the storage tank and will avoid waste heat as the water might cool-off in the pipe without reaching the outlet. The maximum recommended length of domestic uninsulated hot water pipes (with outside diameter of pipe 12-22 mm) should not exceed 12 meter [52]. For case 3 the distribution pipe network was not modelled in great detail as for the typical two homes described in case 1. In order to estimate the heat loss caused from short draw-off's, an average pipe length of seven meters has been assumed for each considered home. The average pipe length represents the average distance from the heat source (boiler/tank) to the points of use of the taps. Other model parameters where applicable are identical to the implementation of case 1.

4 Results

4.1 Measured volume and flowing temperatures

The volume of hot water and flowing temperatures were measured for each home over a period of one year. The top plot on Figure 4 presents the monthly variance of hot water consumption. The monthly variance consumption is calculated based on the monthly consumption from fifteen householders. As presented in the graph, the summer months (July-August) have a slightly lower consumption than the other months which almost have a similar average consumption. The whisker extends on the plot show that the monthly variance consumption is quite high among the householders. The bottom plot presents the total hot water use for each household during a period of one year. The household (H41) with six occupants was expected to have the highest consumption. However, it was not expected that the lowest consumption was from household H42 (where the number of occupants was four). Another surprise was H30 where although there are only two occupants the consumption was significantly higher

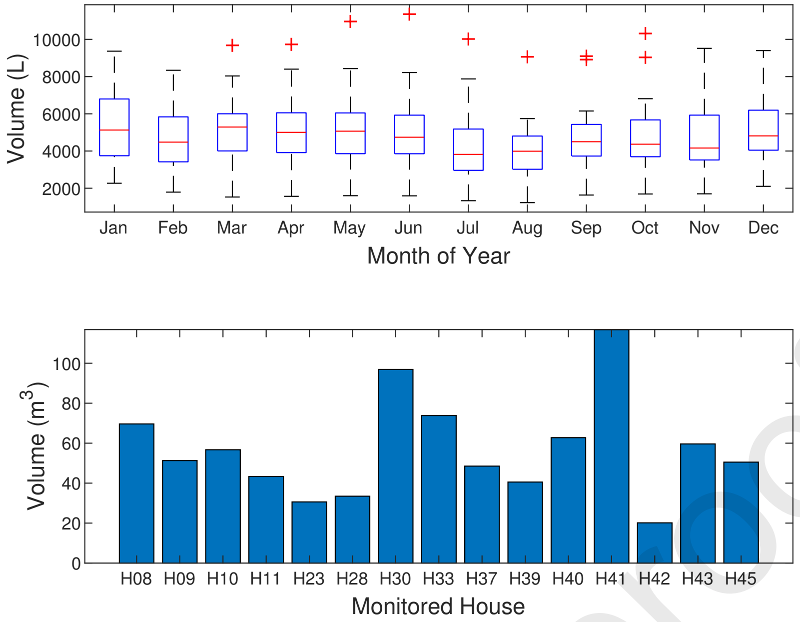

Figure 4: Monthly variance (top) and total year consumption (bottom) of hot water usage.

compared to the other householders; in particular considering H42 where for both cases the hot water for shower is provided from a combi-boiler system. In this context, the user behaviour is shown to have a high impact on the hot water use.

Figure 5 present the relation between the volume of hot water used and the duration of the drawn-offs. It accounts the cumulative of volume (as percentage of the total of volume used) as function of the drawn-offs durations grouped in ten seconds increment duration intervals. As shown in the figure, there is a variation across homes, as for example for drawn-offs less than or equal to fifty seconds long, the cumulative percentage varies from 10% to 70% of the total hot water used. the variation noted in the graph is the attribution of some factors including users behaviour, type of the hot water system, shower type and if the home use dishwasher or not. As can be noted, homes with power shower (H08, H11, H23, H28, H39, H41, H45) have a higher cumulative volume percentage compared to others because the hot water used for showering (that usually have longer drawn-offs) has not been measured and consequently not estimated in calculations.

A comparison of the water supply outlet temperatures from the combi and tank (regular) boiler is presented in Figure 6. As expected, the tank system has a higher supply hot water temperature than the combi-boiler. Each scatter point represents the average temperature of a certain draw-off duration interval. For short draw-off intervals (as can be seen from the figure) the combi-boiler has a lower temperature. As the duration of draw-off gets higher the mean supply temperature also gets higher. Meanwhile for the tank system the supply temperature is more widespread and not dependent from the draw-off duration as much as in the case of the boiler. In analogy to the water supply temperature, the investigation of the flow rate is different between the two systems as presented in Figure 7. This reveals that the combi-boiler has a higher flow rate than the tank system. On average the boiler system has a 30% higher flow rate than the tank system.

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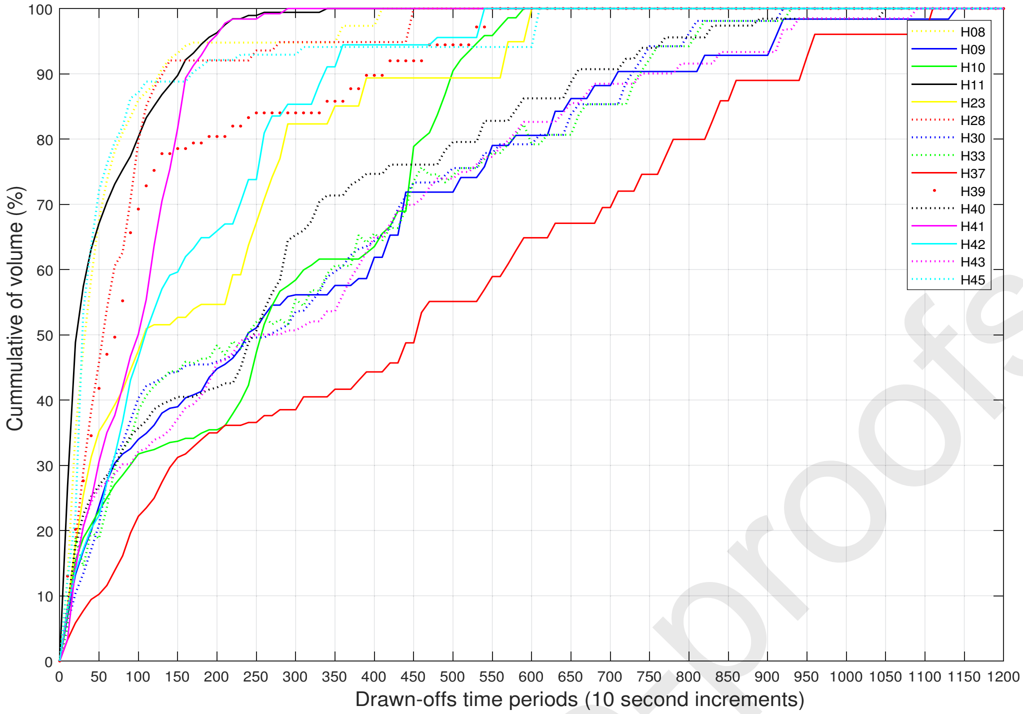

Figure 5: Relation between the cumulative volume of hot water used and duration of drawn-offs time intervals for each home.

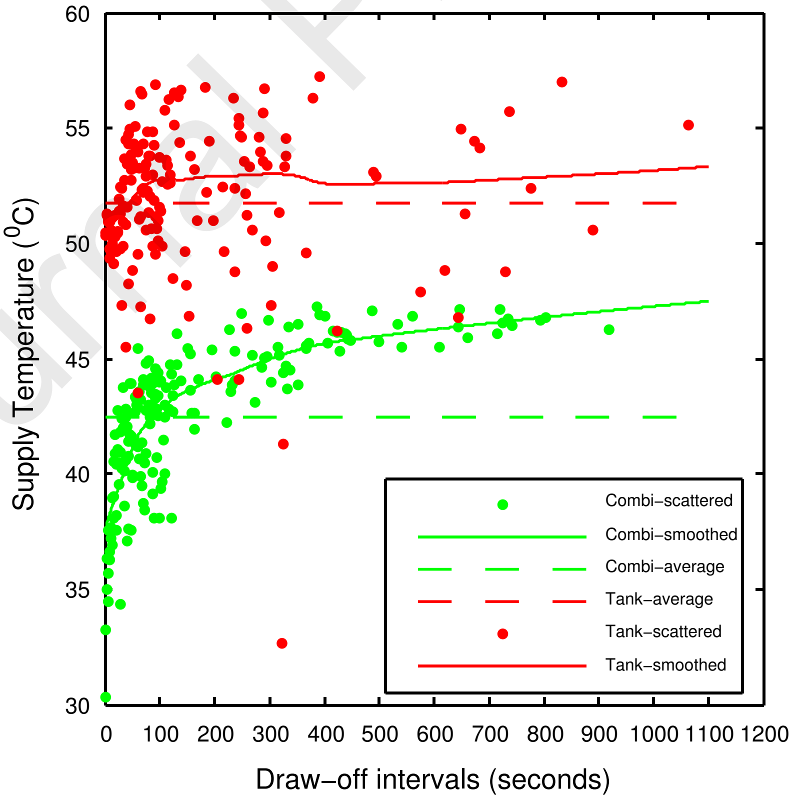

Figure 6: Combi vs. Tank system temperature flows comparison.

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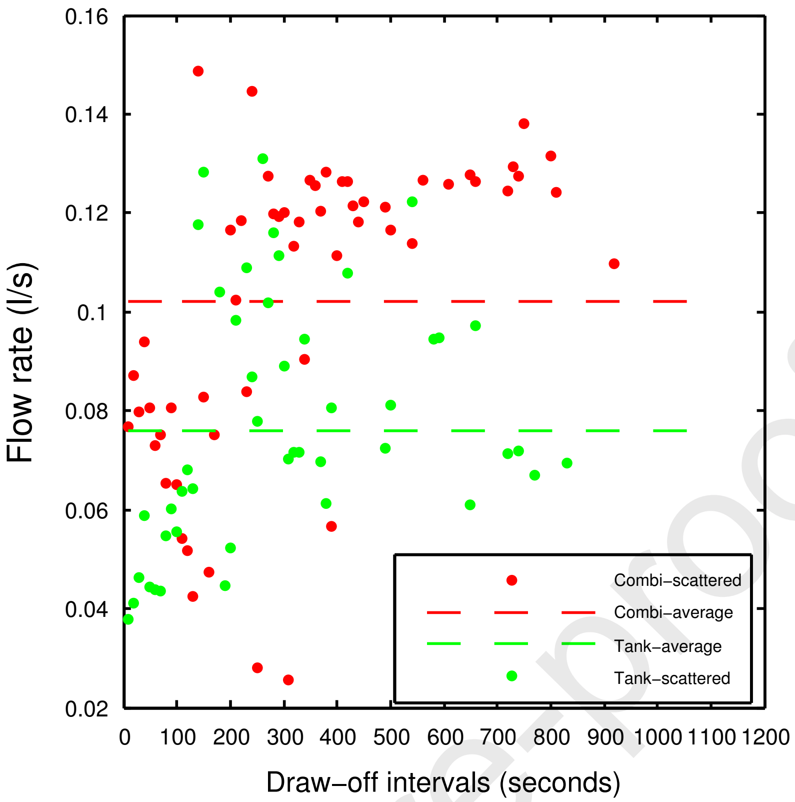

Figure 7: Combi vs. Tank water flow rates comparison.

4.2 Model Validation

In order to validate the accuracy of the results, the outcome of the simulation is compared against the measurements. Figure 8 shows the comparison of the temperature drop (T_{hwt2}) as estimated from the model and the measured temperature during the cool-off conditions after a draw. As can bee seen, the trend of the temperature drop estimated from the model is very similar and close to the measured temperature. At the end of the cool-off time period, the estimated temperature is about 2 ℃ lower as compared with the measured. Based on the measured temperature that drops from 47 to 22 ℃ the discrepancy between simulated and measured is less than 7% which can be an acceptable value when comparing simulated versus measured data. The difference might be caused by the ambient temperature that is considered at 20 ℃ which might be lower than the real ambient temperature in the home. The difference could also be due to any inaccuracy of the hot water volume that is cooled-off inside the pipe although the real distribution system is simulated.

4.3 Case 1- Heat loss estimation

In the modelling, the heat loss from the pipe network in H37 and the network and storage tank in H41 (case 1) have been estimated using the monitored temperature and DHW flow rates data (for the respective home) for a typical day. Figure 9 depicts the heat loss during flowing and zero flowing conditions for the combination boiler (H37) . The blue line represents the heat input to the pipe network and the red the heat loss rate. After each draw-off, the cooling characteristics can be observed.

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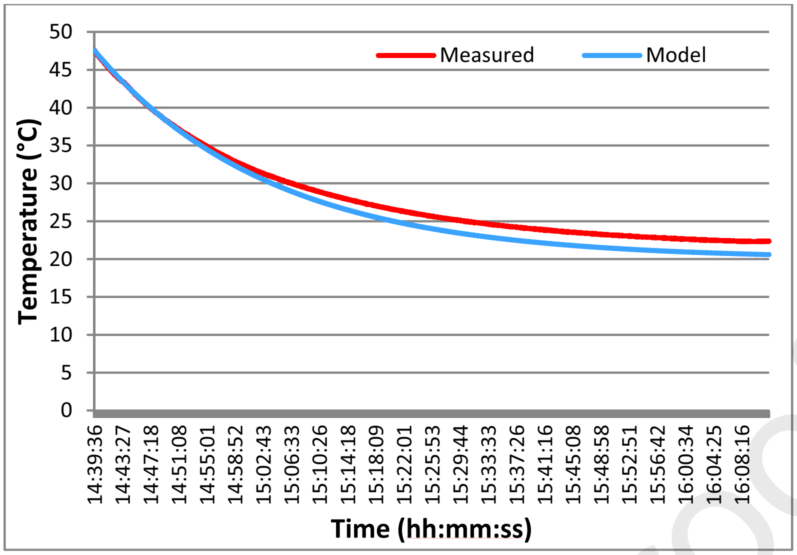

Figure 8: Comparison of the temperature drop between measured and simulated.

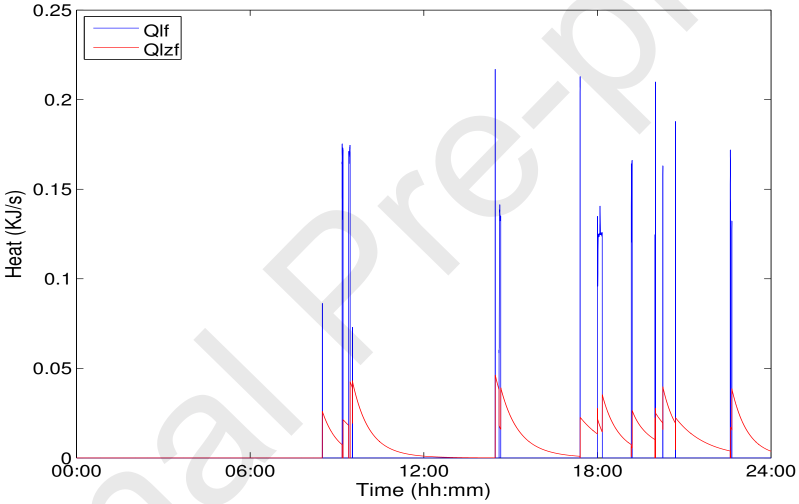

Figure 9: Estimated heat loss during flow and zero-flow conditions for the combination boiler system (H37).

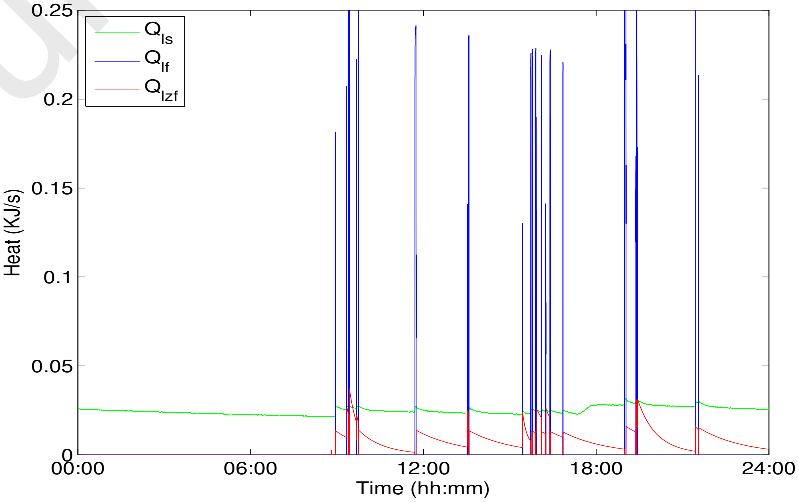

Figure 10: Estimated heat loss during flow and zero-flow conditions for the tank system (H41)

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Table 5: Estimation of heat supplied and heat loss for H37 with (combi-boiler) and H41 (tank system).

		H37 (Combi)		**H41 (Tank)**	
		(KJ)	(%)	(KJ)	(%)
Heat supplied	$\mathbf{Q_{sp}}$	18762	-	9323	-
Heat loss	$\mathbf{Q_{lf}}$	163	1	232	3
distribution	$\mathbf{Q_{lzf}}$	631	3	491	5
system	$\mathbf{Q_{ld}}$	794	4	723	8
Heat loss storage	$\mathbf{Q_{ls}}$	-	-	2151	23
Total heat loss	$\mathbf{Q_{lt}}$	794	4	2874	31

Similarly, the heat loss from the tank system (H41) is shown in Figure 10 with the addition of the green line that represents the losses from the tank. Note that heat loss from the storage tank is continual, varying with water temperature and that the heat loss during flow conditions is higher than under zero flow conditions because of the increase in heat transfer in the inside of the pipe.

Table 5 shows a summary of the total supplied heat and disaggregation of heat losses for each of the two cases. The percentage values show the amount of heat that has been lost as a percentage of the total supplied heat. For example, for the case of a combi-boiler the total heat loss (Q_{lt})) is 4% of total supplied heat (Q_{ls})) where 1% is lost during flowing conditions and 3% during zero-flowing. The total heat loss from the case of the tank system accounts for about 31% of the total supplied heat where 23% of the heat is lost from the storage tank and about 8% is lost from the distribution system.

The supplied heat and the heat loss for H37 is dominated by the more sustained 'showering' draw-offs. The heat loss during zero-flow conditions is considerable even for short draw-offs ('taps') and it is influenced by the hot water is stored in the pipe legs between two successive draw-offs. Similar for H41 the supplied heat and heat loss during flowing condition are dominated from the longest draw-off duration which in this case are the 'sink' draw-offs. The heat loss during zero flow conditions are significantly higher than the heat loss under flow conditions, however the tank losses dominate the overall system heat loss. Figure 11 shows the disaggregation of the volume of water used and the heat loss from the distribution system for H37. The volume of hot water use (top plot left) is dominated by the shower, followed by sink and a small percentage (3%) is used from taps, however the disaggregation of total heat loss (top plot right) reveals that most of the heat loss is caused from the short tap draw-offs: in fact 40%. The top plot (left) shows the disaggregation of heat loss during flowing conditions and it can be noted that the heat loss during flowing conditions dominates the longer (showering/bathing) draw-offs. Despite this, the heat loss during flow conditions is only about 20% of the total heat loss. The rest of the heat is lost during zero-flowing (cool-down) conditions depicted in the bottom right hand plot. As it can be noted, 49% of the heat loss during zero-flowing condition is due to the shorter tap draw-offs. The bottom plot (right) shows the disaggregation of the total heat losses from the distribution system where the heat loss due to taps draw-off has the highest rate overall.

Figure 12 shows the results for H41. The volume of use (top left plot) is disaggregated between taps and sinks,

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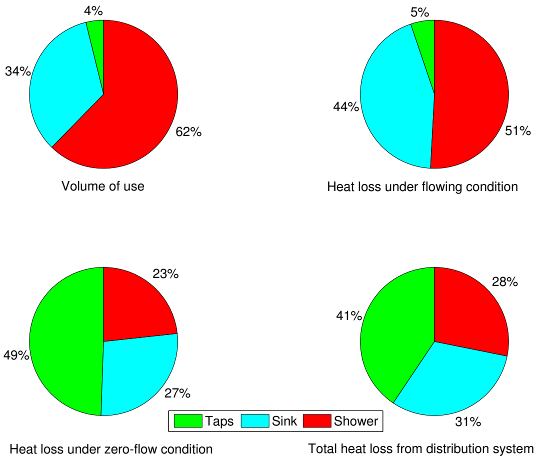

Figure 11: Disaggregation of volume use and heat lost for H37 (combi-boiler).

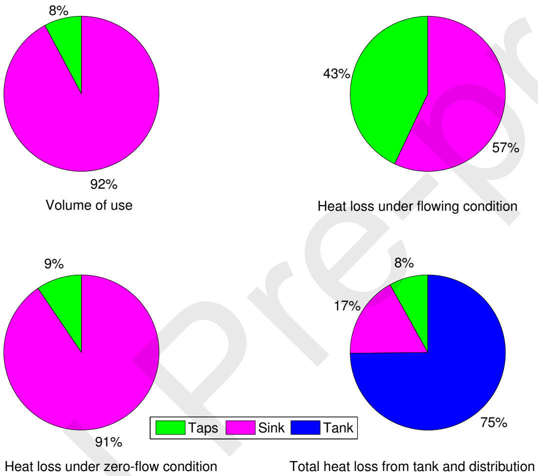

Figure 12: Disaggregation of volume use and heat loss for H41 (tank).

the heat loss plot (bottom right) includes the tank. Although the heat loss during flow conditions (top plot right) is dominated by the sink draw-offs (91%), again the shorter draw-offs impact on the heat loss at zero flow conditions. Clearly, the total heat loss (bottom plot right) is dominated by the storage tank accounting about 77% of the total system heat loss. Heat losses from the storage cylinder dominate the overall heat losses from the hot water system as the volume of hot water stored inside the cylinder is about 120 litres, whilst the volume of hot water that can be 'stored' inside the distribution pipeline is approximately 4-5 litres. The storage cylinder is heated up periodically and kept at 60-65 °C. Heat loss occurs over 24 hours, meanwhile the heat loss from the distribution pipeline happens intermittently when draw-offs take place and during cool-down periods. If the storage hot water cylinder would not have been insulated, the heat losses would have been significantly higher and the differences compared to the distribution system would be even higher.

4.4 Case 2 - Heat loss reductions from interventions

Two interventions have been considered and undertaken: the first intervention considered insulating the distribution pipeline; the second intervention considered a reduction of the pipe length by one metre (where all draw-offs take

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Table 6: Estimated potential saving through insulation and shorter length interventions

Intervention	**Heat Loss (KJ)**		**Savings (%)**
Insulation	$Q_{ld_{uninsulated}}$	912.5	39.7
	$Q_{ld_{insulated}}$	552.1	
Shorter Length (-1m)	$Q_{ld_{Ltotal}}$	912.5	12.5
	$Q_{ld_{Ltotal(-1m)}}$	798	

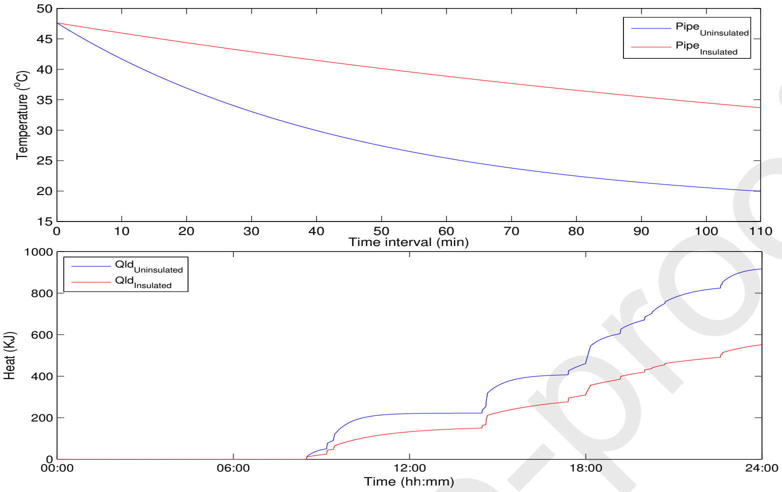

Figure 13: Comparison of temperature drop between insulated and uninsulated distribution pipe.

place) i.e. by moving the boiler one metre closer to the kitchen sink. The interventions were carried out for H37 (equipped with a combi-boiler system). Figure 13 shows the effect of the insulation on the temperature drop of the water in the pipe. The top plot shows how the temperature drops in the distribution pipe line during a zero-flowing condition (cooling-down) time period. For the same cooling-off time period, the temperature of the water in the uninsulated pipe drops from 48°C to 20°C while for the insulated pipe the temperature drops to about 35°C. The bottom plot shows the heat loss from the distribution as estimated for an insulated and an uninsulated pipe during a typical day considered in the simulation. As expected, the insulation of the pipe slows down the cooling-off process reducing the heat loss in the environment. The intervention of shortening the pipe length was considered in the first meter of the pipe segment after the hot water leaves the boiler where all the draws take place. This is the case in practice where the boiler might be moved closer to the kitchen sink. Table 6 shows the total heat loss during a typical day before and after the interventions (insulation and shorter pipe length) take place. Considerable heat loss reductions (up to 40%) can be achieved by insulating the pipe. Some reductions (up to 12%) can be achieved by shorting the pipe length by one meter.

4.5 Case 3 - Impact of short draw-offs on heat loss

The estimated heat loss caused from short draw-offs (considered in the modelling assumptions section) is presented in figures 14, 15, 16, and 17. The heat loss and frequency of draw-offs are estimated based on a year time period of measured data. Figure 14 on the top plot shows the average heat loss from the distribution system for each

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litre of hot water, while the bottom plot shows the average frequency of draw-offs per day as a function of the draw-off duration intervals. The estimated heat loss ranges from 3 (kJ/l) up to 11 (kJ/l) with an average heat loss of 5 (kJ/l) across all houses. Results show that houses with higher short draw-off frequencies (i.e H11 and H43) not necessarily will have the highest heat loss from the distribution system. The heat loss can be considerably influenced by the time gap between successive draw-offs, water supply temperature and water mass flow rate. Houses with a storage tank hot water system (H23 and H28) have a higher supply temperature compared to houses with a combi-boiler system. Results show that these homes have higher heat loss rates compared to other homes. The water mass flow rate also influences the heat loss (i.e H42). Although H42 has a combi-boiler system with a lower supply temperature compared to a storage tank system, it had the lowest mass flow rate while the heat loss rate was high compared to the other homes. The bottom plot shows the frequency of the draw-offs as a function of the drawn durations. The draw-off durations are classified into ten second time periods and the frequency shows the ”percentages” that each classified duration takes place during the whole year. For example the ten second long draw-offs have the highest frequency (across all homes) that range from 6 to 31 of the total draws. This can be explained by the fact that most of the draws take place for hand washing. These are usually quite short. As the durations of the draws get longer the frequency decreases. An increase can be noted for draws with durations from 60 to 180 seconds across all homes and this can be the case of the showering draw-offs as they have usually a length longer than one minute.

Figure 15 on the top plot shows the relationship between the total estimated heat loss and the total volume of hot water used across a whole year monitored period. Each of the data points present the estimated heat loss, hot water used and the frequency of draw-offs for a home. The data are spread and for some houses (although the volume of use is higher) the heat loss is lower meaning that the volume of use is not the crucial parameter. However the fit line shows the trend of the relationship between the heat loss and volume of hot water used. The bottom plot shows the heat loss as a function of daily average draw-off frequencies and estimated losses. These are even more spread compared to the estimated heat loss based on the total volume of hot water used. The plot shows that there is no very good correlation between heat loss and draw off frequencies as it can be seen from the fit and confidence bound lines. In this context, the estimated heat loss rate is considerably influenced by the water temperature and mass flow rates rather than the average draw-off frequencies occurring during the day. Often short draw-offs (i.e hand washing) are considered as draw-offs where the hot water hardly can reach the tap especially for cases where the pipe length between boiler/tank and tap is long. In order to investigate possible savings by ”cutting off” short draw-offs (i.e use of cold water instead of hot water or installing an electric device at a tap for hot water production) the frequencies of less than or equal to 10 second duration were removed from the measured patterns of hot water use in all monitored homes and the model was re-run.

Figure 16 shows the correlation of heat loss with full draw-off frequencies and without draw-off frequencies less than or equal to 10 seconds duration. Each data point presents the heat loss from each house with full (and without) short draw-offs. The fit line shows a good correlation from the new results. The energy loss can be reduced from

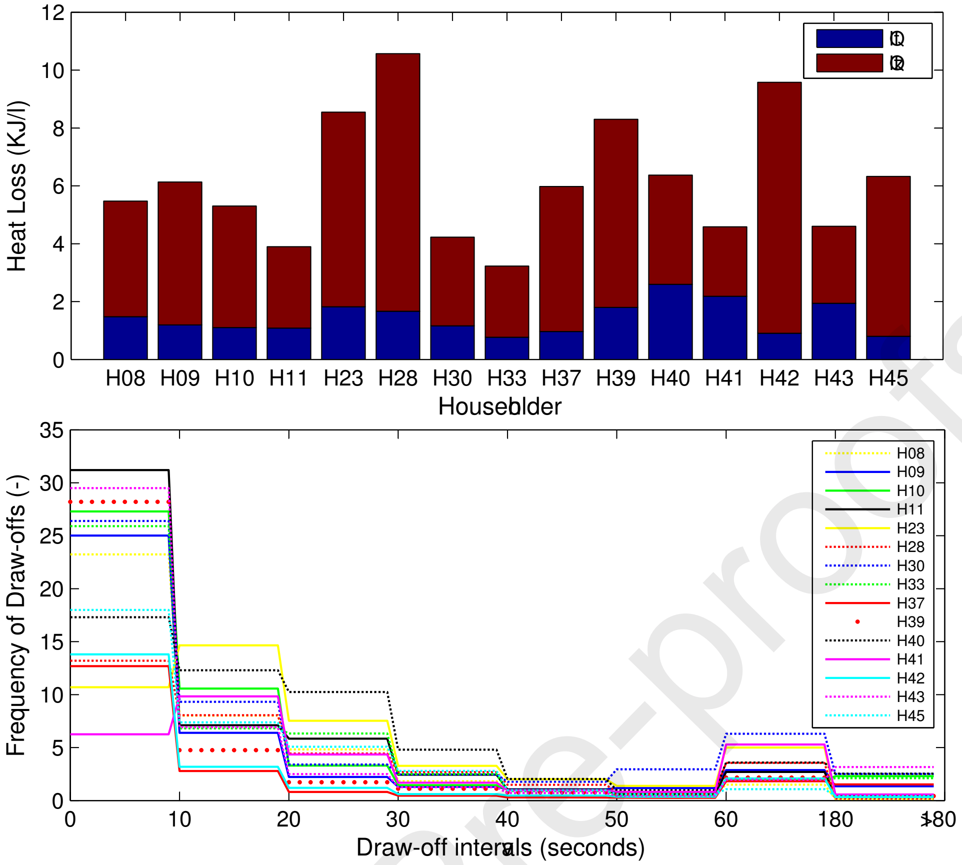

Figure 14: Heat loss per litre (top plot) and draw-offs frequency as function of duration (bottom plot).

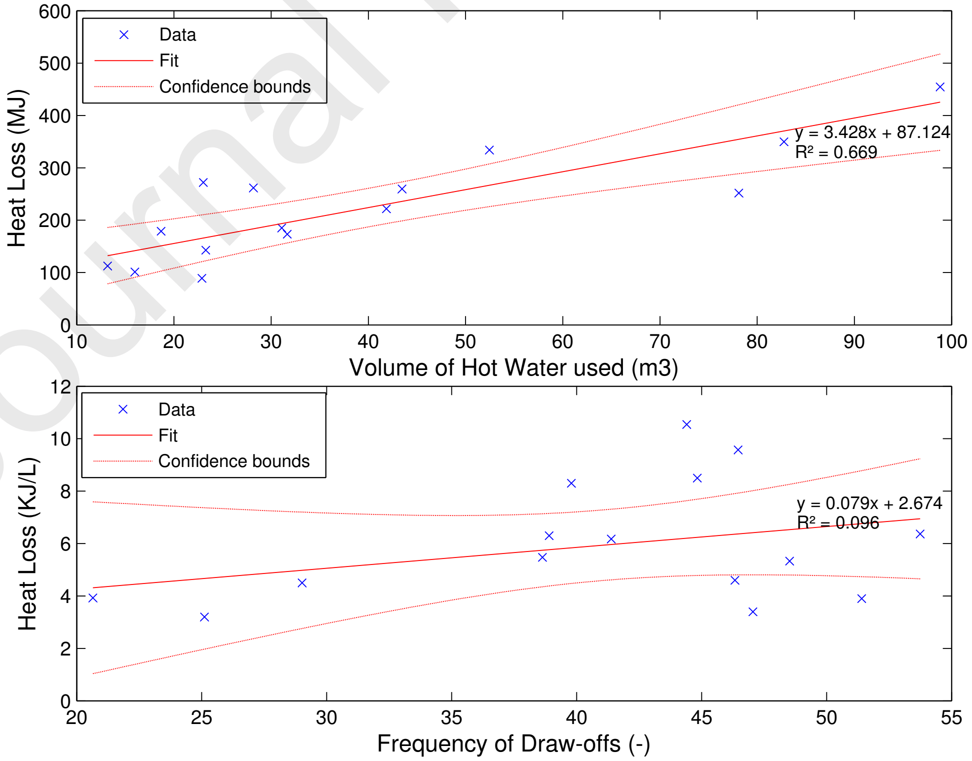

Figure 15: Heat loss vs.volume (top plot) and heat loss vs. draw-offs frequency (bottom plot).

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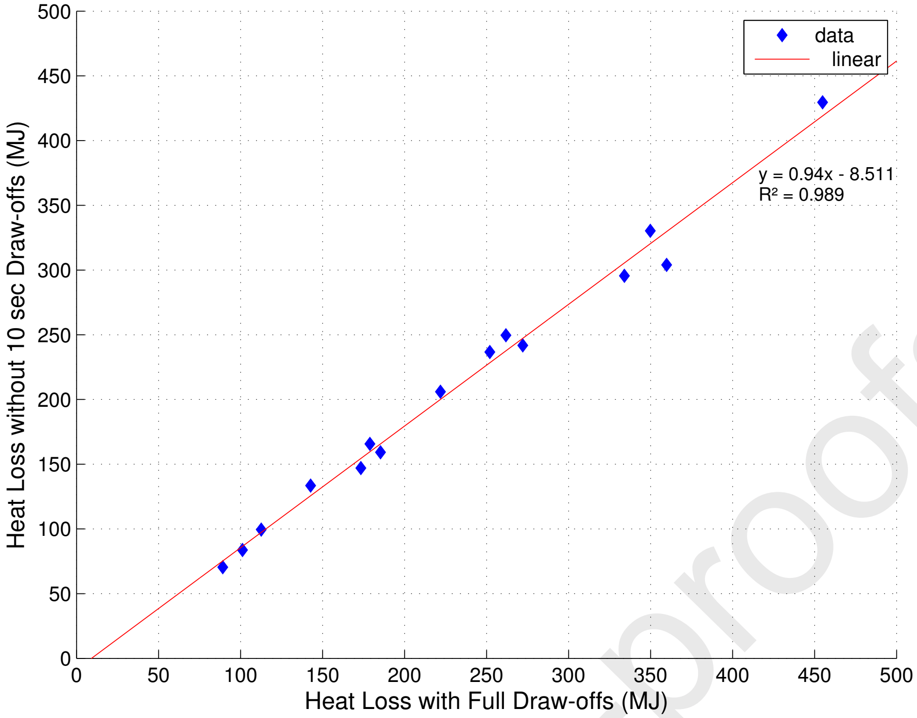

Figure 16: Relationship between heat loss with full draw-offs and without less or equal 10 seconds draw-offs frequencies.

2% up to about 9% for the observed houses. Figure 17 presents the total estimated heat loss during: full draw-offs, cutting-off 10 seconds draw-off frequencies and potential savings from cutting-off intervention. The bar graphs show heat losses (readable on the left ordinate axis) while the line graph shows potential savings (readable on the right ordinate axis). Cutting off draw-offs less than or equal to ten seconds the savings range from about 5% up to 22% across all houses with an average of about 12% heat loss reduction. Considering that the distribution pipe network average length of the distribution network has been considered seven meter for all homes, the variation on the potential savings of the heat loss could be attributed to the water supply temperature, water mass flow rate and characteristic of hot water use patterns such as the time period between successive draw-offs.

5 Discussions

Estimating heat loss from hot water distribution systems is a complex task as the calculation involves several static constants and dynamic variables. While the static constants are more easy to obtain and to incorporate in the model, the dynamic variables are more difficult as they vary over time. While the hot water flow rate and flowing temperature has been measured at the outlet of the boiler/storage tank, they have not been measured at the outlet of each draw-off point and this could be classified as a lack of the measurements for 'feeding' the model inputs. The disaggregation of water flow from boiler/tank outlet to each draw-off point is complex and it might not represent the reality in the system. However with assumptions made (case 1) we believe that the considered approach is very sensitive and a good estimation on the disaggregation of the water flow. Moreover, it was necessary that the water flow temperature was linked to the water flow rates and the respective dead legs in order to estimate accurately the

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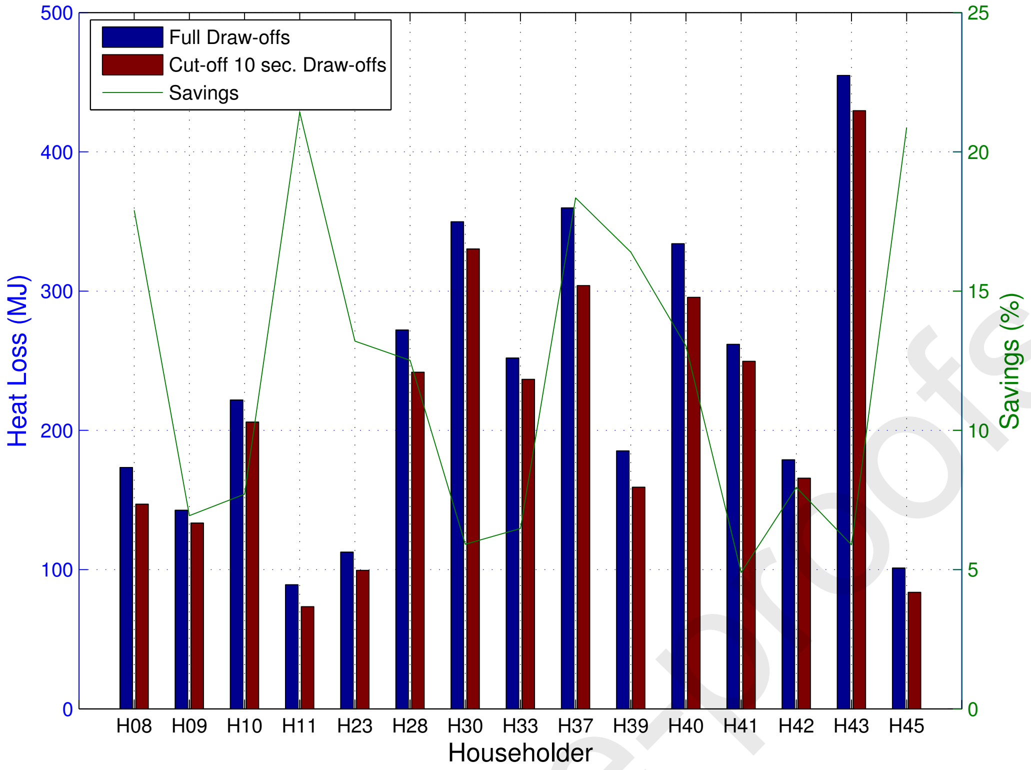

Figure 17: Total heat loss: full draw-offs vs. without lees or equal 10 seconds draw-offs frequencies and percentage savings.

heat loss. To be more confident and in order to control this process, this was the reason why we chose a typical day for running the simulation scenario in case 1. The model validation shows that the estimated results are within an acceptable error range and consequently the estimated results are quite accurate. For case 2 and 3, it was not necessary to disaggregate the water flow rate and the simulations were run for a year time period.

In our results, the measured water supply temperature ranged between 45-57 °C for a regular boiler with storage cylinder and between 35-47 °C for a combi-boiler, resulting in lower temperatures compared with suggestions from regulations [11], i.e. 60 °C for stored water and 50 °C for the distribution supply temperature [12]. This discrepancy could be caused by the design set point temperature or be based on the fact that the storage water is heated up periodically and not synchronised with the measured outlet temperature. For very short draw-offs, the combi-boiler has a lower supply temperature, whilst for longer draw-offs the temperature is higher. Hence, the boiler needs a certain time period to achieve the set-point outlet supply temperature. Heat losses from the hot water cylinder amounted to around 23% of the total supplied heat. This number is very close compared to other studies. For example, Pratt et.al [15] and [17] assumed that heat losses from the hot water storage cylinder would be around 24% . In terms of the distribution system, heat losses were about 8% in this study. These are lower when compared with another study [31] that estimated heat losses in a range of 10-40%. This discrepancy might be due to modelling uncertainty or uncertainty in the underlying assumptions that eventually are leading to increased heat losses. Insulating the distribution pipe reduced the heat losses by about 40%. In comparison, [36] found that

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insulation could reduce heat losses by 7-13%. This difference is because our model estimated heat losses in the distribution pipe during flowing and non-flowing conditions, whilst the other study estimated heat loss only when water is during the flowing conditions, therefore ignoring the standing (cool-down) heat losses.

Besides the heat losses from the hot water system due to temperature decay in the pipeline or the hot water cylinder, waste of hot water and consequently heat loss could also happen due to the water leakage. The water research foundation's report [53] highlighted that water leakage from domestic hot water systems amounts to 13% of a households indoor water, whilst another study [54] estimated that customer post meter leakage accounts for up to 10% of the total water consumption, particularly in the residential sector. In this research, water leakage has not been measured or estimated for that matter, however it is recommended to consider additional heat losses due to water leakage. In order to minimise and avoid water leakage, the hot water cylinder and all distribution pipes should be protected from corrosion predominantly caused by the water hardness. Hard water is formed when water percolates through deposits of limestone, chalk or gypsum which are largely made up of calcium and magnesium carbonates. Sacrificial or power anodes can be used to protect hot water system from corrosion. Future work in this direction could focus on enhancing the developed model to automatically disaggregate the water flowing to distribution system at each outlet tap by introducing a preset condition/criteria based on the duration of draw-offs, for example. This more complex model would be even closer to reality and represent the behaviour of the distribution system. Also, to minimise the discrepancy estimated in the validation section, the model might need to be improved and redeveloped to consider the ambient air temperature as a changing variable rather than a constant. The hot water distribution pipelines might be exposed and heated by sunlight radiation. However, in practice, only small parts of the distribution system might be exposed to this condition and if so, only for a short period of time. Incorporating this phenomenon into the model would tackle this uncertainty.

6 Conclusion

An analytical dynamic simulation model was developed to estimate waste heat from a distribution pipe network and storage tank in domestic hot water systems. The developed model is based on the Log Mean Temperature Difference (LMTD) calculation method and under realistic conditions can estimate heat losses by applying high resolution secondly time-step water supply temperature and flow rates measured from real homes. The model is validated against measured data. It is shown that it can obtain heat losses of less than 7% discrepancy. The developed model was used to estimate heat losses from fifteen homes, investigating the following in more details: heat losses from typical hot water systems with combi-boiler and regular boiler with storage cylinder; impact of insulation and shortening the pipe length on heat loss reductions; and impact of short draw-offs (less than or equal to ten seconds long).

Key observations and findings from simulations were as follows:

Households hot water usage ranged from 55 l/day to 328 l/day across the considered homes. The hot water supply temperature for combi-boiler ranged from 35 ℃ for short draw-offs up to 47 ℃ for longer draw-offs, and for about 45-57 ℃ for a regular boiler with hot water storage cylinder system. Water flow rates on average were about 0.1

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l/s and 0.8 l/s for combi-boiler and regular boiler system, respectively. Draw-offs less than or equal to fifty second long accounted for 10 to 70 % of the total hot water used.

Key observations and findings from simulations were as follows:

The results for heat losses for a typical day were around 0.8 MJ for the hot water system with a combi-boiler and 2.8 MJ for the hot water system with a regular boiler and hot water storage cylinder. The proportion of the waste heat of the heat supplied to hot water production was about 4% for the case with a combi-boiler system and about 31% in the case of a regular boiler with the storage tank system. To put this into context, the total DHW energy consumption was 13% of the annual gas consumption for the hot water system for the combi- boiler system and 20% for the storage tank system, respectively (9% and 13% of total). Insulating the pipe network can reduce losses up to 45%. Moving the boiler (and effectively reducing the pipe length by 1m) can yield to reductions of 29%. Applying both could potentially generate a reduction of 60% in waste heat. Waste heat from short draw-offs is significant because hot water is drawn into the distribution network and left to cool. It would seem that short draw-offs can be responsible for 40% of heat loss. Avoiding hot water used for very short draw-offs of less than or equal to ten seconds, the heat loss in the distribution pipe network can be reduced from 5 to 25% depending on the water supply temperature, water mass flow rate and characteristic of successive draw-off patterns. In summary, potential savings can be achieved on the waste heat through a combination of energy reduction measures such as; applying insulation to the pipe network; moving the boiler more closer to the centre of the network; "avoiding" hot water used from very short draw-offs. This should consider for example a change of user behaviour (for example such as use of cold water just for washing hands instead of hot hater) or technology improvements such as heating hot water at point of use or implementation of intelligent controls that based on the duration of the draw-offs can control the operation of the heat generator and water supply from the system. Future work might consider the following: to further develop the analytical model in order to automatically disaggregate the water flowing to distribution system; to improve the model by considering ambient air temperature as a varying variable rather than a constant; and to consider heat gains from solar radiation in the system.

7 Acknowledgement

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A Appendix: Calculation algorithm for estimating heat loss from the hot water pipe

```
%% Load data
x=load('H37AllYear.csv');
t  = unixtime2mat(x(:,1));
mf  = x(:,3);
tin  = x(:,5); % water temperature inlet (mains) to the boiler
```

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```
tout  = x(:,4); % water temperature outlet to the boiler (DHW supply temperature)

%% Specify constants

Cpw = 4.186; % water specific heat
pi = 3.14;  % pi constant
e = 2.71;  % Euler constant
Rpin = 0.018;  % pipe inside radius
dp = 0.006;  % pipe thickenees
Cco = 0.384;  %copper pipe specific heat
Rhoco = 8940; %copper pipe density
UAzf= 0.672; %heat loss factor under zero-flowing
UAf= 0.762; %heat loss factor under flowing
Vp = 1.6; %pipe volume for a 6 m long
Lp= 7;  % pipe length
Tair = 20;  %environment air temperature

%% Filtering data

mfr=zeros(length(mf),1);
for i=1:length(mf)
    if tin(i)== -99 || tout(i)==-99
        mfr(i)=-99;
    else
        mfr(i) = mf(i);
    end
end

flow=zeros(length(mfr),1);
for i=1:length(mfr)
    if mfr(i)<= 0.009
        flow(i)=0;
    else
        flow(i) = mfr(i);
    end
```

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```
end

%% calculation loop for estimating heat losses in the pipe
network during flowing and non-flowing water conditions

coolcnt = -1;
M=0;
T_hot_t2=zeros(length(mfr),1);
T_hot_out=zeros(length(mfr),1);
m=zeros(length(mfr),1);
Qlf=zeros(length(mfr),1);
Qlzf=zeros(length(mfr),1);
dtempfl=zeros(length(mfr),1);
dtempzfl=zeros(length(T_hot_t2),1);

for i = 1:length(flow)
    if flow(i)==-99
        continue;
    elseif flow(i)==0
        if coolcnt>-1
            coolcnt=coolcnt+1;
            if M>=1.6
                M=1.6;
            end
            if tout(i) > -99
      T_hot_t2(i)=Tair+(tout(i-coolcnt)-Tair)*exp(-((UAzf*coolcnt)/(M*Cpw*Cco*1000)));
             else
              tout(i) = -99;
              T_hot_t2(i) = 0;
            end
            if T_hot_t2(i) > -99
            Qlzf(i)=M./1000*Cpw*Cco*(T_hot_t2(i)-Tair);
            else
                T_hot_t2(i) = -99;
                Qlzf(i)= 0;
```

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```
            end
            flow(i)=M;
            if Qlzf(i) <0
                Qlzf(i) = 0;
            else Qlzf(i) = Qlzf(i);
            end
        end
        else
        if coolcnt>0
            M=0;
        end
        M=flow(i)+M;
        if tout(i) ~= -99
        T_hot_out(i)=Tair+(tout(i)-Tair)*exp(-((UAf*Lp)/(flow(i)*Cpw*1000)));
        else
        tout(i) = -99;
        T_hot_out(i) = 0;
        end
        if T_hot_out(i)>0
            dtempfl(i) = -(T_hot_out(i)-tout(i));
            Qlf(i) = (dtempfl(i)*Cpw.*flow(i));
            elseif T_hot_out(i)==0
                dtempfl(i) = 0;
                Qlf(i) = 0;
        end
        coolcnt=0;
        flow(i)=M;
    end
end.
```

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