ESTIMATING WASTE HEAT FROM DOMESTIC HOT WATER SYSTEMS IN UK DWELLINGS

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ABSTRACT

Domestic Hot Water (DHW) production can account for a quarter of the energy consumed in UK dwellings and this proportion is likely to increase as the energy required for space heating reduces in order to achieve demand reduction targets. As the margins for improving the performance of heating system technologies diminish, the need for improving modelling accuracy and precision increases. Although studies have considered DHW use, there is a lack of reflection on the consumption and performance of systems in contemporary UK dwellings. This paper is based on two family homes and investigates heat losses from DHW networks using high resolution demand data combined with an analytical model. The model estimates are compared to widely used building performance models and it is found that the models may over estimate the heat losses by a significant amount and that short draw-offs are particularity influential in determining the amount of heat wasted.

BACKGROUND

Water heating accounts for 26% of the total energy consumed in UK residential homes (DECC, 2012). Interest is growing in both targeting consumption and waste, once fabric and heating system gains are maximised and in understanding the impact that DHW might have on delivering load shifting in demand side management schemes.

In the UK, the most significant attempt to tackle the standing losses associated with DHW storage tanks has been the move to replace old systems with gas fired combination boilers that provide instantaneous supply. Although older boilers can have a heat generation efficiency of up to 81%, the actual delivered heat efficiency can drop to 38%, or even lower depending on the draw-off characteristics (EST, 2009). As of 2010, 45% of homes in the UK have a combination boiler (DECC, 2010).

Factors such as plumbing layout, pipe sizing and location, hot water use quantity and patterns, and insulation levels of pipework have also been shown to be significant in determining the effectiveness of the delivered heat (Kershaw et al., 2010; Lutz et al., 2011; Maguire et al., 2011). Despite these studies, however, important questions remain around understanding operational efficiency of both tanked and combination based systems, the position of the boiler/tank in relation to the draw off points, the effect of the (almost universal) lack of pipework installation and the effect of the draw-off characteristics associated with specific users. All these factors vary from home to home and it is unclear as to how current modelling and performance tools treat waste heat from DHW systems when compared to installations in real homes in the UK.

This paper examines two typical UK homes and places DHW consumption and potential energy reductions in context with that reported in the literature. The work examines how each system network performs in terms of heat loss: one of these is a traditional tanked storage system and the other a combination boiler based system. The hot water distribution networks are modelled based on ASHRAE methods to provide a benchmark of expected performance and this analytical solution is then used to compare the system losses estimated by: EnergyPlus, PHPP, SAP and SBEM. This work builds on critical review of hot water modelling techniques also presented at BS2015 (Marini et al., 2015).

METHODOLOGY

The analysis is centered around typical, mid-sized, owner-occupied family homes in the UK, monitored as part of a 4 year investigation into demand reduction in the home[1]. The study reported here focuses on two homes from the study based on 2013 data, referred to here by their project codes.

H37 is a detached house built in the 1970s, it has been extended from the original layout and has 12 rooms excluding hall and landing. Double glazing and additional insulation has been installed. Mother, Father and two teenage children (8-13) live there. The heating system was upgraded in 2008 with the extension work when the old tanked system and boiler was removed and replaced with a combination boiler. The renovations 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 home built in the 1960s and has been extended with a conservatory. It has 10 rooms including the conservatory and has been double glazed and had additional insulation installed. Mother, Fa-

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

ther, 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 and open vent storage tank. There is a main bathroom and an en-suite, both of which have electric showers.

Both homes represent very real system and fabric history and highlights 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. DHW volume flow and temperatures were sampled every second over to year period alongside ambient temperatures in the home.

A typical intervention reduction analysis might be to explore the effect of insulating the hot water distribution pipework, or to measure the effect of moving the boiler from the bedroom (which is some distance from the bathroom and kitchen) to a location more central in the distribution network. Understanding the energy reduction achieved through the removal of the traditional tanked system might also be of interest. To evaluate these changes, models of the DHW system networks for H37 and H41 are developed based on ASHRAE methods ASHRAE (2007) using heat loss factors derived from experimental work by C.C Hiller (2005); C.C. Hiller (2006) described here.

Heat supplied to hot water

The hot water flow rate was measured via an in-line turbine meter placed on the cold water feed to the boiler/tank in H37/H41. The surface temperatures of the copper pipes at these inlets and outlets points were used to indicate the water temperature and hence to estimate the supplied heat using,

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

DHW tank heat loss

For the case when water stored at 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 losses 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.

Pipe network heat loss

When hot water flows from the boiler or 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,

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

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,

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

Equations (6) and (7) determine the heat lost from the pipe network during flowing 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

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

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

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) present the upper limits (maximum) of heat loss and are valid only if the cooling-off of the standing water in the pipe is complete ($T_{hw\,t_2} = T_a$). It should be noted that heat loss and temperature drop are not constant along the length of the network because the temperature of each successive length of the pipe is less than one before it and applies to both flow conditions. The pipe temperature decays exponentially, hence the use of LMTD.

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 maximum volume V (l) of the branch pipe length, then M value is equal to V (l) otherwise the 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 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 calculation was the same as the resolution of the data: 1 second.

The water temperature entering pipe $(T_{hot_{in}})$, room air temperature (T_{air}) and water flow rate $(\dot{m})$ are parameters that were measured. The calculation assumes the air temperature is constant although an average ambient air temperature been estimated from the monitoring data in order to model the conditions in the home more precisely.

The total heat lost in the DHW distribution network for H37 (combination boiler) is estimated by, $Q_{lt} = Q_{lf} + Q_{lzf}$ and by $Q_{lt} = Q_{lf} + Q_{lzf} + Q_{ls}$, for the tank system in H41.

Model parameters

The pipe networks in H37 and H41, depicted in Figure 1, differ in terms of geometrical layout and draw-off points served. H37 has five draw-offs including a sink tap (ground floor), two taps and a shower in bathroom (first floor) and one tap in toilet (ground floor). H41 has two taps in the bathroom (first floor) and one sink tap (ground floor). The references in Figure 1 relate to the details given in Table 1. Table 2 presents the thermal properties of water, pipe material and insulation and Table 3 details the heat loss factors for typical pipe diameters under flow and zero-flow conditions with different thicknesses of insulation.

Modelling assumptions

The heat supplied and lost has been estimated based on a typical day. The hot water volume flow rate was measured at the outlet of boiler/tank and hence disaggregation to 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 ≤15s, flow occurs at a tap

$ELSEIF$ ≥15s AND ≤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 es-

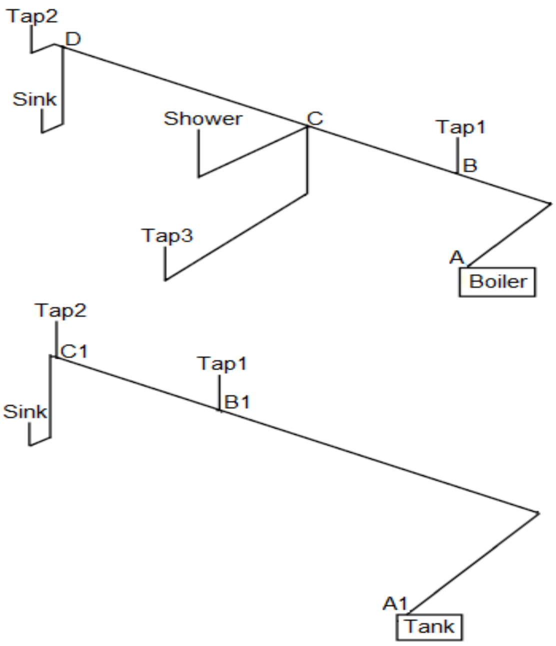

Figure 1: Hot water distribution network for H37 (top) and H41 (bottom).

Table 1: 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 2: Thermal property values for water, copper and foam insulation.

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

Table 3: Copper piping heat loss factors

Diameter (mm)	Insulation (mm)	UA_{zf} ($\mathrm{Wm^{-1}K^{-1}}$)	UA_f ($\mathrm{Wm^{-1}K^{-1}}$)
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)

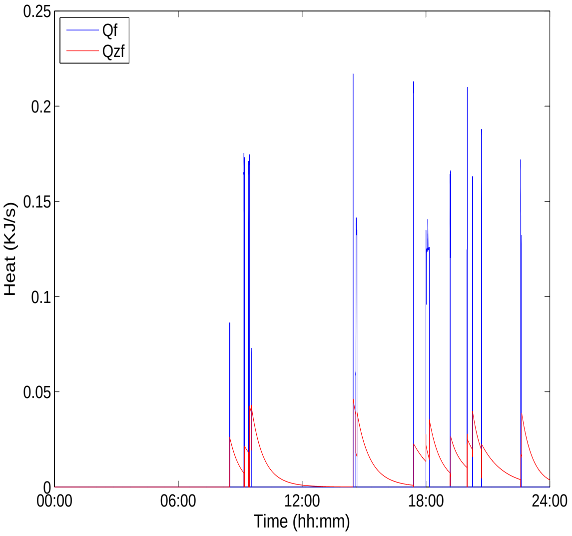

Figure 2: Estimated heat lost during flow and zero-flow conditions for the combination boiler system (H37).

timate the heat transfer from the pipe network into the the space. The temperature surrounding the tank was considered constant at 20°C, stratification was neglected.

MODEL VALIDATION

Heat lost from the pipe network in H37 and the network and storage tank in H41 have been estimated using the monitored temperature and DHW volume flow rate data. Figure 2 depicts the heat loss during flowing and zero flowing conditions for the combination boiler case. 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.

Similarly, the tank system in H41 is shown in Figure 3 with the addition of the green line that represents the losses from the tank. Note that the heat loss from the storage tank is continual, varying with water temperature and that the heat loss during flow conditions are higher than under zero flow conditions because of the increase in heat transfer on the inside of the pipe. Figure 4 shows the effect of insulation on modelled temperature drop during cooling.

RESULTS

Table 4 shows the estimated supplied heat and heat loss during each draw-off for H37. The supplied

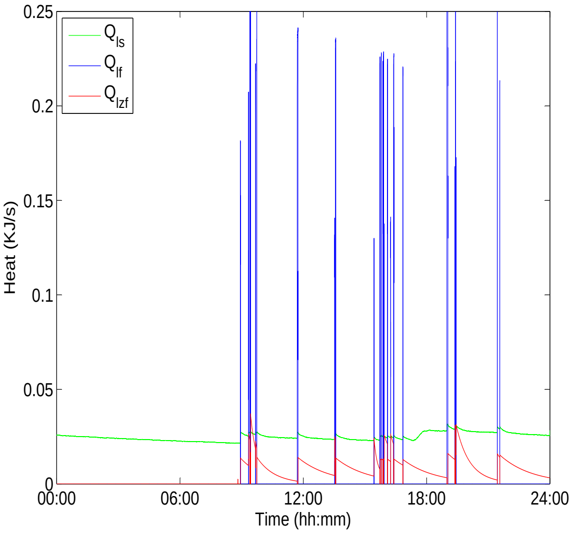

Figure 3: Estimated heat lost during flow and zero-flow conditions for the tank system (H41)

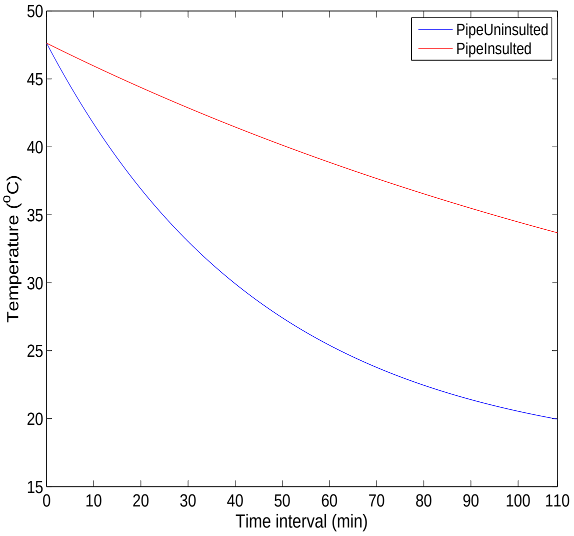

Figure 4: Comparison of temperature drop between insulated and uninsulated distribution pipe.

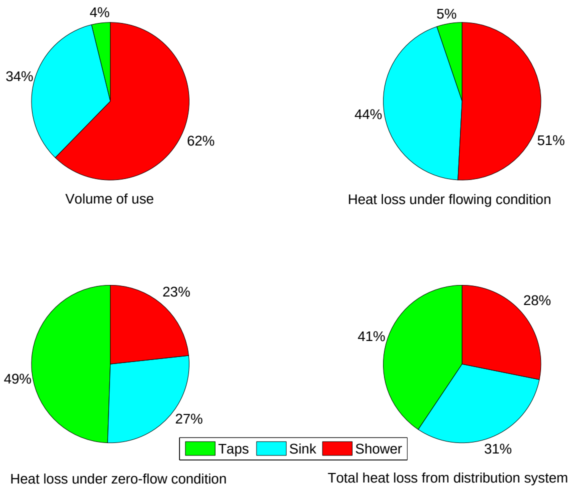

Figure 5: Disaggregation of volume use and heat lost for H37 (combination boiler).

heat and heat lost 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 that cools in water that has been stored in the pipe legs between two successive draw-offs. The total heat lost as a percentage of supply, $Q_{lt} = 4\%$.

Table 5 presents the results for H41, which includes the losses from the tank. Similar to the previous case, the supplied heat and heat lost are dominated from the longest draw-off durations which in this case are the ‘sink’ draw-offs. The heat loss during zero flow conditions are significantly higher than heat lost under flow conditions, however the tank losses dominate in this system. The heat lost from tank occurs over the whole 24 hour period as the water temperature is always above 45°C. In this context the heat lost from the tank during the first draw-off (08:56) present the cumulative heat lost from the storage tank from the last draw-off (21:33). In this system, the total heat lost as a percentage of supply, $Q_{lt} = 31\%$.

Figure 5 shows the disaggregation of volume of water used and the heat loss from distribution system for H37. The volume of hot water use (top plot left) is dominated by shower, followed by sink and a small percentage (3%) is used from taps, however the disaggregation of total heat lost (top plot right) reveal that most of the heat lost is caused from the short tap draw-offs: in fact 40%.

The bottom plot (left) show the disaggregation of heat loss during flowing conditions and as can be noted the heat loss is during flowing conditions dominates in the longer (showering/bathing) draw-offs. Despite this, the heat lost during flow conditions is only about 20% of total heat lost, the rest of the heat is lost during cooling (zero-flow) conditions, depicted in the bottom right hand plot. 49% of the cooling heat loss is due to the shorter, tap draw-offs.

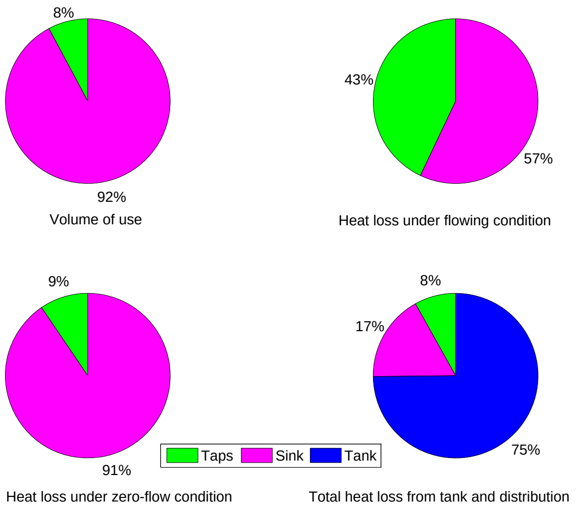

Figure 6: Disaggregation of volume use and heat lost for H41 (tank).

Figure 6 Gives the results for H41. The volume of use (top left plot) is disaggregated between taps and sink, the heat loss plot (bottom right) includes the tank. Although the heat lost 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 lost (bottom plot right) is dominated by the tank accounting, which accounts for about 77% of the total.

Reduction measures

Two energy reduction measures were applied to H37, and their impact calculated using the analytical model:

- applying insulation to the pipe network;
- moving the boiler to the center of the network;
- and, the combined effect of the measures.

Insulating pipe network can be reduce losses up to 45%, moving the boiler (effectively reducing the pipe length by 2m) can yield reductions of 29% and applying both could potentially generate a reduction of 60% in waste heat.

Tool comparison

Some simulation tools are more detailed in their treatment of hot water distribution networks than others. A review of simulated tools, input parameters considered for simulation and analysis are presented in (Marini et al., 2015).

In this paper, the combination boiler system in H37 was modelled with a number of commonly used dynamic and static simulation software packages in order to compare the estimated heat loss with that derived from the analytical model. Table 6 presents the results, where significant over estimation of heat lost is observed.

The differences between analytical model and simulated tools are influenced by the choice input parameters and from differences in the calculation methodol-

Table 4: Estimated supplied and heat lost for H37 (combi) system.

Time (hr:mm)	**Dead Leg** -	**Draw-off duration** (seconds)	**Volume** (litre)	$\mathbf{Q_{sp}}$ (KJ)	$\mathbf{Q_{lf}}$ (KJ)	$\mathbf{Q_{lzf}}$ (KJ)	$\mathbf{Q_{ld}}$ (KJ)
08:29	Boiler-Tap1	7	0.56	62.7	0.6	38.4	39.0
09:10	Boiler-Sink	110	10.7	1381.4	16.7	12.4	22.3
09:24	Boiler-Sink	184	15.5	2352.5	29.4	32.2	61.6
09:32	Boiler-Tap1	10	1.1	148.1	0.7	70.4	80.1
14:28	Boiler-Tap3	8	0.57	68.5	2.7	56.2	58.9
14:36	Boiler-Shower	225	20.5	2990.0	30.4	79.5	109.9
17:24	Boiler-Tap3	8	0.47	45.5	1.6	35.0	36.6
17:59	Boiler-Shower	612	60.6	9400.2	52.6	70.0	122.6
19:10	Boiler-Sink	117	11.9	1490.0	15.8	38.9	54.7
19:59	Boiler-Tap2	7	0.3	15.9	0.7	0.9	1.6
20:00	Boiler-Sink	11	1	149.4	2.2	18.8	21.0
20:15	Boiler-Tap2	9	0.94	115.7	1.3	42.5	43.8
20:41	Boiler-Sink	17	1.67	173.6	2.8	66.7	69.5
22:35	Boiler-Sink	32	2.84	263.1	4.3	2.3	6.6
22:38	Boiler-Tap1	8	0.85	105.3	1.0	66.7	66.7
Total	**-**	**1365**	**129.5**	**18761.8**	**162.7**	**630.7**	**793.4**
Loss as % of supply	**-**	**-**	**-**	**-**	**1**	**3**	**4**

Table 5: Estimated supplied and heat lost for H41 (tank) system.

Time (hr:mm)	**Dead Leg** -	**Draw-off duration** (seconds)	**Volume** (litre)	$\mathbf{Q_{sp}}$ (KJ)	$\mathbf{Q_{lf}}$ (KJ)	$\mathbf{Q_{lzf}}$ (KJ)	$\mathbf{Q_{ld}}$ (KJ)	$\mathbf{Q_{ls}}$ (KJ)
08:56	Tank-Tap2	29	1.65	177.6	4.9	16.3	22.2	753.9
09:20	Tank-Tap1	20	0.95	122.8	1.9	5.0	6.9	37.4
09:24	Tank-Sink	77	4.46	664.5	18.2	0.8	19.0	6.1
09:26	Tank-Sink	18	0.58	87.5	3.2	23.4	26.7	3.7
09:40	Tank-Tap2	18	0.29	39.3	2.7	3.7	6.4	23.4
09:43	Tank-Sink	28	0.75	110.9	5.7	39.2	44.9	5.3
11:42	Tank-Sink	143	11.37	1604.9	33.3	52.9	86.2	176.3
13:31	Tank-Tap1	13	0.57	56.7	1.7	2.8	4.5	162.7
13:33	Tank-Sink	100	7.4	1040.3	22.7	52.9	75.6	3.1
15:26	Tank-Tap1	8	0.1	9.7	0.9	1.8	2.7	160.6
15:43	Tank-Sink	54	3.15	385.0	11.4	14.4	25.8	24.0
15:47	Tank-Sink	42	2.55	353.4	8.8	3.5	12.3	6.1
15:52	Tank-Sink	20	0.66	90.0	3.9	0.8	4.7	8.1
15:54	Tank-Sink	36	2.24	315.8	7.7	1.1	8.8	2.1
15:56	Tank-Tap1	7	0.31	4.3	0.8	1.6	2.4	3.1
16:05	Tank-Sink	25	1.44	190.5	5.6	6.6	12.2	14.5
16:15	Tank-Tap1	19	0.6	77.3	2.3	23.3	25.6	13.8
16:23	Tank-Sink	74	5.47	750.0	15.9	17.8	33.7	12.5
16:50	Tank-Sink	30	1.3	159.4	6.0	53.7	59.7	39.4
18:59	Tank-Sink	182	14.65	2279.7	49.2	17.8	67.0	203.7
19:22	Tank-Tap1	14	0.47	65.3	2.2	2.3	4.5	42.4
19:24	Tank-Sink	42	2.51	401.0	10.7	0.8	11.5	2.8
19:25	Tank-Tap1	13	0.21	33.9	2.0	2.6	4.6	2.9
21:26	Tank-Sink	31	1.88	242.9	7.7	78.1	85.8	201.3
21:33	Tank-Tap2	14	0.43	62.1	2.5	57.5	60.0	13.1
Total	**-**	**1055**	**66**	**9324.7**	**231.9**	**490.5**	**722.4**	**2151.4**
Loss as % of supply	**-**	**-**	**-**	**-**	**3**	**5**	**8**	**23**

Table 6: Heat loss comparison between analytical model and simulation tools (based on H37).

Estimated Method	Heat Loss (KJ/L)	Heat Loss (KJ/day)
Analytic Model	6	793
EnergyPlus	18	4680
PHPP[a]	26	3600
SAP[b]	26	8280
SBEM[c]	33	8280

[a] Passive House Planning Package; [b] Standard Assessment Procedure; [c] Simplified Building Energy Model

ogy. Some of the key differences between EnergyPlus are:

Draw-off schedule: EnergyPlus was run with the default DHW demand profile for a year and then daily heat loss calculated from that. More representative characteristics of the specific home were used in the analytical model.

Water mass flow rate: again default values will vary when compared to specific homes.

Boiler outlet temperature: EnergyPlus considers the outlet temperature to be constant, which does not truly represent the case where there are short draw-offs. In the measured data also, the supply temperature from the boiler was lower than that assumed in the simulation.

Draw-off point definition: EnergyPlus assumed that all the draw-offs take place in the same point, to simplify the modelling whereas the analytical model explicitly treated each draw-off. This influences the heat loss estimation as volume of water cooled-down and pipe of length are crucial factors in heat loss calculation.

Calculation procedure: the analytical model used the LMTD to calculate the water temperature drop. EnergyPlus uses a model based on work by Hanby et al. (2002), which estimates the pipe heat transfer by discretizing the pipe length into a number of nodes (20). However, from model description and simulation output results it was found that the model only estimates the heat loss during flow conditions and hence may actually be underestimating losses since the analytical model revealed that most of the heat losses occur under zero-flow conditions.

The static simulation tools do not carry out any detailed calculation for heat losses but rather consider heat loss as a percentage of supplied heat. For example, the SAP and SBEM tools consider the heat loss from distribution system is about 15% and 17% respectively. The estimate in PHPP is based on simplified calculation that, for this case, suggests about 19% is lost. In reality the output results from analytical model demonstrated that the percentage of heat lost appears to be quite a lot lower than the other methods when compared to this particular house.

CONCLUSION

An analytical model of a hot water heating network was presented and used to estimate waste heat under realistic conditions by applying high resolution tapping rates measured in real family homes. The model was used to investigate system heat loss and to assess the assumptions in EnergyPlus, PHPP, SAP and SBEM. The key observations were:

Losses can be reduced by 60%: typical DHW networks in UK dwellings are uninsulated and longer than they need to be. Addressing these issues in a system is likely to yield significant reductions in waste heat.

Waste heat from short draw-offs is significant: because hot water is drawn into the network and left to cool, it would seem that short draw-offs can be responsible for 40% of heat lost.

Current models overestimate losses: all four modelling tools examined overestimated the waste heat attributed to the supply of DHW from 300% to 600%, compared to the analytical model for the cases examined here.

Although the percentages reported above are significant, we should not forget that the proportion of the waste heat is about 4% of the heat supplied to the hot water production in the combination boiler system (H37) and 31% from the tank system (H41). To put this in context, the total DHW energy consumption is 13% and 20% of the annual gas consumption in each home respectively (9% and 13% of total).

Recent studies have shown reductions in energy consumption in the order of 50% or more are likely to be needed if carbon reduction targets are to be met (Cosar Jorda et al., 2015). Better treatment of waste heat and draw-off characteristics will become more important in model based analysis as the assessment of the gains in effectiveness of system performance become ever smaller.

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NOMENCLATURE

Symbols

c_p	specific heat capacity	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	kgs^{-1}
M	mass	kg
r	radius	mm
R	thermal resistance	m^{2}KW^{-1}
Q	thermal heat	KJ
S	surface area	m^2
T	temperature	°C
t_1	initial time	second
t_2	final time	second
V	volume	l
U	heat transfer coefficient	Wm^{-1}K^{-1}
UA	heat loss factor	Wm^{-1}K^{-1}
ρ	density	kgm^{-3}
λ	thermal conductivity	Wm^{-1}K^{-1}
π	constant (pi)	-
ΔT	temperature difference	K

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