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In-situ measurement of heat loss from thermal stores

Paula Morgenstern

MRes Energy Demand in the Built Environment, UCL Energy Institute, London, UK.

Abstract

In district-heated apartments, the heat for hot water provision is often also provided by the central facilities while individual apartments are equipped with thermal stores. Tank manufacturers are required by legislation to declare standing losses for thermal stores, but it is known that these often underestimate actual losses from cylinders and adjoining pipe installations. This paper illustrates the case of a building where residents have repeatedly reported the airing cupboards containing their thermal stores to be “hot enough to back bread in.” A method to estimate the actual heat loss from thermal store and pipes is presented based on measuring the temperature difference between the airing cupboard and the outside before and after the installation of an additional, defined heat source in the cupboard. The actual heat loss can then be used to evaluate the economic benefits of retrofitting or improving insulation measures and therewith enable investment decisions.

Keywords: Actual Heat Loss, Temperature measurements, Thermal store, District heating

1 Introduction

The UK is legally committed to reduce greenhouse gas emissions by 80% from 1990 levels by 2050 (Climate Change Act 2008). A large part of these reductions will have to be achieved in buildings (DECC 2011) and energy efficiency requirements are mandated in Part L of the Building Regulations 2010. Part L also requires fixed building services such as heating and hot water systems to be commissioned “to ensure that they use no more fuel and power than is reasonable in the circumstances (L1B:7)”. It was, however, pointed out that the achieved performance of buildings often lags behind both design and client expectations (Bordass et al 2004, www.carbonbuzz.org). Cohen and his colleagues (2001) have studied this phenomenon extensively in the PROBE series and coined the term ‘performance gap’ for it. For fixed building services, less systematic efforts have been made but there is nevertheless evidence that differences between predicted and actual heat loss can be significant. This paper focusses on performance gaps in thermal stores, which Ward (1979) reports to frequently be over 50%.

One cause for the lack of actual performance data is the complexity of measurements in occupied dwellings due to access issues, disruption and occupancy induced unknown variables (Mumovic & Santamouris 2009). Also, few simple and reliable methods seem to be available. For thermal stores, the legislative document in effect advices that “consideration should be given to standing losses from storage”, but gives no details on measurement procedures approved by the secretary of state (Domestic Building Services Compliance Guide 2010). In industry and academia, two methods are common to measure the standing loss of storage tanks:

- **The constant temperature loss test:** Store manufacturer determine standing losses according to EN 12897:2006 (Annex B) by electrically heating the primary tank to 65±2°C and holding the temperature while metering the consumed electricity during two subsequent days.

- **The decay test:** Standing losses for stores without integral electrical immersion heater can be measured in a "cool down test" (Cruickshank & Harrison 2010). Here, the store is initially charged to a constant temperature and the cooling curve is measured blocking off external sources of heat.

Both methods require more than 48h during which the thermal store cannot be used otherwise. Also, they rely on point temperature measurements which require information about tank stratification to interpolate on heat loss. For these reasons, the practicability of both methods to determine losses of thermal stores in use is limited. Here, a low priced and non-disruptive alternative is presented. The method is used in a case study building to determine the heat loss from the thermal store in the airing cupboard of a district-heated apartment. Limitations to the method are discussed.

2 Proposed method

The proposed heat loss test can be applied to determine heat losses from thermal stores which are effective as heat inputs into airing cupboards or other defined spaces. In its principles, it shows similarities to an electric co-heating test. But while in co-heating a defined amount of heat is introduced into a building to determine the whole house heat loss coefficient, here internal heat gains are the prime focus.

2.1 Mathematical description

The test is based on the measurement of a temperature difference between the inside and the outside of a control volume before and after the introduction of a defined heat source. The knowledge about the amount of heat additionally introduced and the relation of the temperature differences allows for estimating the original heat input into the control volume. Figure 1 shows the experimental set-up for a case where the control volume is an airing cupboard and the heat loss of a thermal store and adjoining pipes are to be determined.

Solving the energy balance for the airing cupboard under steady-state conditions reveals that the relation between the heat input into the cupboard and the resulting temperature difference is linear and connected through the heat loss coefficient of the cupboard. Assuming the heat loss coefficient of the cupboard to be constant over time, both phases of the experiment can be combined (nomenclature as shown in Fig. 1):

$$\frac{Q_1^I}{(T_1^I - T_2^I)} = \frac{Q_1^{II} + Q_2^{II}}{(T_1^{II} - T_2^{II})} \quad \text{or} \quad \frac{Q_1^I}{\Delta T^I} = \frac{Q_1^{II} + Q_2^{II}}{\Delta T^{II}} \tag{1}$$

If the heat input of the additional heat source is known and all temperatures are measured during both phases of the experiment, the original heat input can be calculated (assuming it is not influenced by the additional heat source, $Q_1^I = Q_1^{II} := Q_1$):

$$Q_1 = Q_2 * \frac{\Delta T^I}{\Delta T^{II} - \Delta T^I} \tag{2}$$

2.2 Practical realisation

Sensitivity analysis shows that the resulting heat loss is most strongly influenced by the measured temperature differences. Repeated temperature measurements and the use of confidence intervals are consequently recommended (JCGM, 2008). Ideally, the sensor within the cupboard is to be placed in its core and at medium height. The outside sensor should be situated as close to the door as possible, uninfluenced by solar gains and air movement from ventilation or occupant activity. Depending on the use of the airing cupboard and occupant preference it may not always be possible to place the sensors consistently, this needs to be recorded for data analysis.

Regarding the heat source, any heat source allowing the cupboard door to be kept closed is suitable, but a sufficiently long life time, no fire risk and little noise need to be guaranteed to minimise disruption to the occupant. A realistic estimate of the heat loss expected is essential to dimension the heat source correctly as both should be in the same range for a clear signal. Some thought should be given to how the heat source can be calibrated as errors in heat input are sure enough secondary to errors in temperature measurement but nevertheless influence the validity of the results.

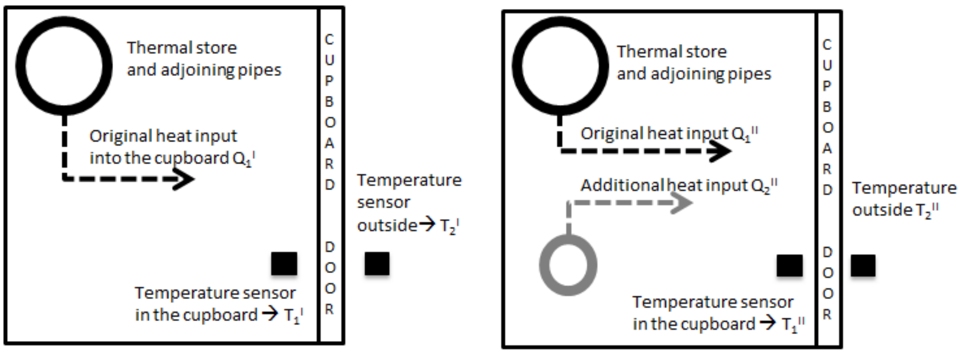

Figure 1: Experimental set-up of heat loss test (a) (left) Phase I: Measuring the original temperature difference caused by heat loss from thermal store and adjoining pipes, b) (right) Phase II: Measuring an increased temperature difference caused by heat losses as previously and additional heat input)

3 Application of method

A single-case study is used to prove the feasibility of the proposed in-situ heat loss test. Especially if working with single cases their selection is crucial and information-orientated sampling can help to increase generalizability (Devin-Wright 2012). For this study, an "extreme case (Flyvbjerg 2006)" is selected: a building whose residents have repeatedly reported their airing cupboards to be "hot enough to back bread in."

3.1 The case study building

The case study building is a 1960's mixed-use development in Central London. Apart from a residential section with almost 400 flats, the building contains a shopping center on the ground floor. The residential section of the building is served by a gas-fired district heating providing space heating and hot water to the residents. Each flat is equipped with a 130 liters thermal store (2010 Gledhill Torrent Indirect-OV) situated in an airing cupboard of approximately 1.5m^2 floor space.

3.2 Data collection

Temperature measurements: HOBO® temperature sensors measure the temperature in and outside the airing cupboard of one flat in 10 minute intervals during a total of two weeks (one week for each experimental phase). While the inside sensor can be placed as planned, the outside sensor location has to be adapted because no suitable place can be found in extreme proximity to the cupboard door. Instead, the sensor is placed in a bookshelf in 1.5m distance to the cupboard, notwithstanding protected from solar or internal gains and draughts.

Additional heat source: A commercial 120W portable flood light is used as additional heat source. It is plugged into a socket next to the airing cupboard and the cable is carefully passed below the airing cupboard door. To determine the heat input from the lamp, power consumption and bulb efficiency have are determined. A second identical bulb is calibrated in the laboratory by manually recording its electricity consumption as displayed by a conventional plug-in mains power and energy monitor. Due to the ageing of the light bulb, the power consumption declines from initially 126W to the 120W indicated by the light bulb manufacturer after 300h. For the airing cupboard experiment, the light bulb is used 164.3h resulting in an average power consumption of 124.4W during this period if inter-bulb variation is neglected. No efficiency for this particular bulb is known, but according to GE Lighting (n.d.) the efficiency of halogen light bulbs generally ranges around 90%. Therefore the additional heat input into the cupboard from the lamp is 111.9W.

3.3 Actual heat loss in case study airing cupboards

Figure 2 shows the temperature profiles for both phases of the experiment. The installation of the lamp half-way through the experiment results in a significant increase of the temperature inside the airing cupboard, while the temperature outside the cupboard is almost constant and only influenced by daily variation in the ambient temperature outside.

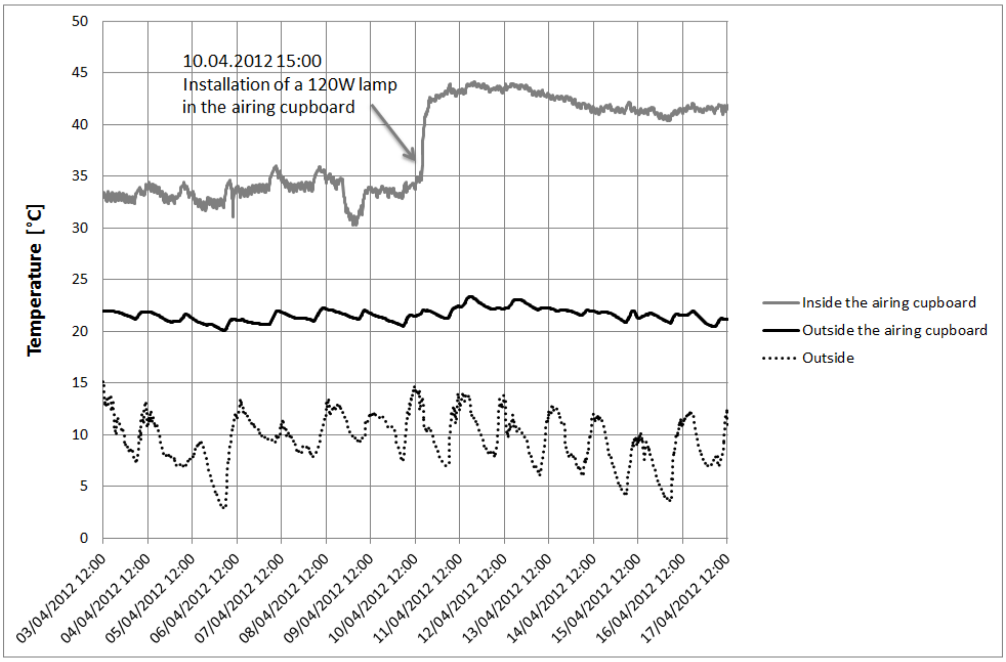

Figure 2: Field temperatures without and with additional heat source

The Kolmogorov-Smirnov Test for normality shows that the recorded temperature data series are not normal distributed, ruling out the use of means and standard deviations to characterise them. Consequently, medians are preferred (baseline case) and a lower and an upper limit for ΔT^{I} and ΔT^{II} are calculated based on the 5% and 95% percentiles of the individual temperature series. With these, the heat loss of the thermal store and the adjoining pipes can then be calculated using (2) and results as shown in Table 1. The analysis confirms that in all cases the heat loss is higher than it should be for a best-practice installation according to manufacturer data (store only, heat loss from insulated pipework is assumed to be negligible).

3.4 Cost-Benefit-Analysis of retrofitting insulation

Knowledge about the actual heat loss from installations in the airing cupboard is essential to assess the economic viability of insulation improvements. The presented method provides an accurate estimate (including 95% confidence margins) of the actual heat loss. However, other methods have to be used to assess the principle sources of heat loss and the costs of retrofitting insulation have to be estimated accordingly. For the case study building, a professional quote for improvements to the insulation of the airing cupboards assumes a cost of £150 per cupboard. A net present value (NPV) analysis based on the 2011/2012 local cost of heat to residents of 6.5 p/kWh and a customer discount rate of 5% (Wilson & Dowlatabadi 2007) is carried out to determine the payback time of such an investment based on the potential heat loss reductions as given in Table 1. It is thereby not taken into account that as an unintended consequence of insulation improvements in the airing cupboards, space heating demand during winter might go up and full savings can only effectively be realised outside the heating season.

Table 1: Estimated heat loss of thermal store and adjoining pipes in the case study building

	Lower limit	**Baseline case**	**Upper limit**
Actual heat loss as computed from (2) [kWh/d]	**3.24**	**4.16**	**4.83**
Best practise heat loss as given by thermal store manufacturer [kWh/d]	2.80	2.80	2.80
Payback time of insulation improvements [yrs] (NPV analysis, customer discount rate 5%)	23	5	3

4 Discussion and conclusions

The field experiment in the case study building can be seen as pilot to demonstrate the functionality of the developed heat loss test. In the future, a more thorough field trial involving more than one flat as well as different buildings will be helpful to refine the methodology. However, the pilot succeeded both in proving the usefulness of the test to enable investment decisions and in highlighting some limitations of the current proceeding.

4.1 Further applications

As shown for the case study building, the proposed method allows estimating in-use heat losses inside closed control volumes in an easy and non-disruptive way. Occupants are hardly affected by the measurement and can carry on using heating and hot water as usual, offering the additional chance of picking up on behaviour induced particularities in comparative tests. The resulting estimates for the actual heat loss are directly usable to evaluate the cost effectiveness of retrofit measures. This helps to reduce the risk of investments, something widely acknowledged as main barrier to the uptake of energy-efficiency measures (Christie, Donn & Walton 2011).

In this paper, the developed heat loss test was applied to a thermal store in a district-heated flat. But the test method is not restricted to such: it could be applied to any enclosed control volume in which heat inputs are to be quantified as long as a suitable additional heat source can be found and installed. District heating mains running through stairwells for example might be another application for the test, expanding its use outside the domestic context. Moreover, the method can also be used outside the field of district heating. In the UK, the prevailing application of thermal stores is the embedding of alternative energy, primarily solar thermal heating and heat pumps which from this year are supported by the government through the Renewable Heat Incentive (DECC 2011a). With an increasing number of thermal store installations, knowledge about their actual heat loss becomes crucial to achieve carbon targets.

4.2 *Limitations to the proposed method*

Table 2 lists both general limitations to the proposed heat loss test and practical shortcomings in the case study building. While the former will persist as they are intrinsic to the approach, the later are improvable through better experimental design.

Table 2: Limitations to the proposed method in descending order of importance

General due to idealised assumptions	**Case study building field trial**
The system is assumed to be in steady state during each phase of the experiment, but the store heat loss actually depends on realised heat requirements and response speed of the store control afterwards.	*Temperature measurements:* Only one data logger each is used to record temperatures. Ideally and if the project budget allows so, more loggers in every space could minimise error from convective air movement.
Uniform temperatures within the whole control volume and outside are assumed, but in reality spatial temperature variation will occur e.g. due to tank stratification, ventilation practises and occupant activity.	*Cost-benefit-analysis:* The manufacturer loss factor is based on 45K temperature difference between store and ambient, but the real store temperature is unknown. Ideally, it should be recorded to allow for better comparison.
The control volume heat loss coefficient is assumed to be constant, but (also because temperature sensors can sometimes not be positioned as planned due to furnishing or occupant preferences) the measured coefficient is subject to air movement.	*Additional heat source:* Heat output may vary between halogen bulbs affecting the applicability of the calibration data. Bulb efficiency could not be measured and the power meter used is very basic. Ideally, the heat source should be calibrated more directly.

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