Energy and Built Environment xxx (xxxx) xxx

Contents lists available at ScienceDirect

Energy and Built Environment

journal homepage: http://www.keaipublishing.com/en/journals/energy-and-built-environment/

An assessment for the viability of recovering heat from a smoke extract system

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A R T I C L E I N F O

Keywords:
Smoke heat recovery
Smoke extract process
Heat transfer
Soot thermal efficiency

A B S T R A C T

Over the course of industrial manufacturing, additional heat within the extract systems is usually released into the atmosphere and its intrinsic energy is wasted. This paper investigated a cold abatement smoke extract system for a fire testing wall furnace to determine the viability in recovering heat from the hot smoke. Three scenarios were investigated: 1) the extract system was closed and only 300°C smoke was present; 2) the system took in ambient air around the furnace and heat recovery occurred at 80°C in smoky air; 3) the smoke had been removed from the air and the temperature was 60°C. It was found that there was a significant build-up of soot on Scenarios 1 & 2 with a build-up rate of 0.25 μm/s which totalled 2.7 mm of soot after a three-hour test. The soot had a low heat transfer rate and therefore acted as an insulator on the heat exchanger which reduced the efficiency significantly of it over time. Due to this loss in efficiency, it was more viable to recover heat in Scenario 3 at 60°C in clean air than it was to recover heat at 300°C or 80°C in smoky air. The results show that having clean air was more important than a higher temperature when it came from recovering heat from a cold abatement system for a fire testing furnace. This paper contributes to reveal the possibilities of harnessing the "waste heat" for use in other applications in the vicinity of the manufacturing processes, such as heating water within a central heating plant, domestic hot water or electricity generation, or re-cycled within the industrial plant itself.

1. Introduction

For many industrial processes, rising energy prices and reducing the environmental impact of global warming are major challenges, and energy efficiency is becoming a crucial success factor [1]. Statistics show that global energy consumption will grow 20-30 % over the next 20 years, through increased demand and economic growth, but also through the needs to invest in, and deliver from renewable energy sources [2]. The manufacturing industry is one of the most energy consuming ones, and therefore has the most potential to have hot extract systems and provide environmental benefits through secondary processing the outputs of the primary systems [3]. Many manufactural sites have a considerable unexploited potential for energy savings and a recent report from the International Energy Agency [4] states the industrial plants throughout the world are using about 50% more energy than necessary. This over-use of energy coupled with the potential for significantly higher prices results in a greater need to explore energy use optimisation in the design of systems for all industrial settings, as this will enable less energy usage and therefore less funds being wasted.

In fact, many extract systems used in industry can contain more heat than the ambient air due to the heat generated in their underlying processes [5]. The additional heat within these extract systems is usually released into the atmosphere and its intrinsic energy is wasted. This heat could be harnessed for use in other applications in the vicinity of the manufacturing processes, such as heating water within a central heating plant, domestic hot water or electricity generation, and re-cycled within the industrial plant itself. However, most of the heat is wasted from industrial processes such as the process using a furnace, which has not received much attention [6]. Fundamentally, this could be mitigated by recovering waste heat using heat exchangers, which is a promising approach to boosting the energy efficiency [7,8]. In exploring the intrinsic energy for the furnace there could be some consideration of how generic features of the design could be incorporated into other relatively bespoke systems. The premise for exploring the potential for incorporating a system to harness the heat from a fire test system is that high temperatures observed within the extract system of the furnaces could lead to heat being recovered [9], however, there are issues to be resolved with this air since the exhaust from the furnace is typically filled smoke

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https://doi.org/10.1016/j.enbenv.2022.03.003
Received 10 January 2022; Received in revised form 23 February 2022; Accepted 5 March 2022
Available online xxx

Nomenclature

Symbols

c	heat exchanger efficiency [-]
c_p	specific heat capacity [kJ/kg•K]
k	thermal conductivity [W/m•K]
l	material thickness [m]
$\dot{m}$	mass flowrate [kg/s]
Q	energy transferred [W]
R_1	material 1 thermal resistance [m^2•K/W]
R_2	material 2 thermal resistance [m^2•K/W]
Rn	material n thermal resistance [m^2•K/W]
R_{si}	internal thermal resistance [m^2•K/W]
R_{so}	external thermal resistance [m^2•K/W]
R_T	combined thermal resistance [m^2•K/W]
T	temperature [K]
T_1	fluid one hot temperature [K]
T_2	fluid one cold temperature [K]
t_1	fluid two cold temperature [K]
t_2	fluid two hot temperature [K]
$U - value$	heat transfer coefficient [W/m^2•K]

Greek symbols

ΔT	temperature difference [K]
ΔT_m	log mean temperature [K]

Abbreviations

AHU	air handling unit
BS	British Standards
BSI	British Standards Institution
ESP	electrostatic precipitator
LPHW	low pressure hot water
LTHW	low temperature hot water

which also needs to be removed prior to release into the atmosphere [10].

Fig. 1 provides an outline illustration of the components of a typical fire test system and its surrounding environment. The energy and cost saving, and environmental benefits are normally expected to be correlated with the flow of heat in the process and the aim would be to cost effectively recover maximum amounts of energy to be used within the immediate vicinity to the test. This has the potential to have enough energy, for example, to heat an adjacent office or provide hot water for domestic needs. The locations for where heat recovery could take place is demonstrated in Fig. 2 [11] based upon the commercially available facilities.

Studies point out that to make sure that products and buildings meet the relevant fire resistance strategies, their materials and constructions need to be tested [12]. All fire tests using the furnace are all conducted in the same manner, as set out in BS EN 1363-1 [13] to ensure that the specimens meet the standards irrespective of the material under test. The test itself assesses the behaviour of the specimen of building construction when it is put under defined heating and pressure conditions. The typical furnace as shown in Fig. 2, is powered by natural gas and have a 3 m x 3 m section of wall, or component within a wall, built into a standardised frame as if it were being built into a building [11]. The completed frame is then fixed to the front of the furnace to create a seal and the test commences with heat and pressure being applied to one side.

A key element of the issues to be resolved in harnessing the energy potential from the fire test system is the nature of smoke produced from the tests in the furnace. Cuce et al [14]. found that the smoke particles contained in the gas exhaust from the furnace vary in properties depending on the material being tested and will impact on the efficiency of heat recovery. It was reported that smoke contains a mixture of various gases and particles and is the result of incomplete combustion [15].

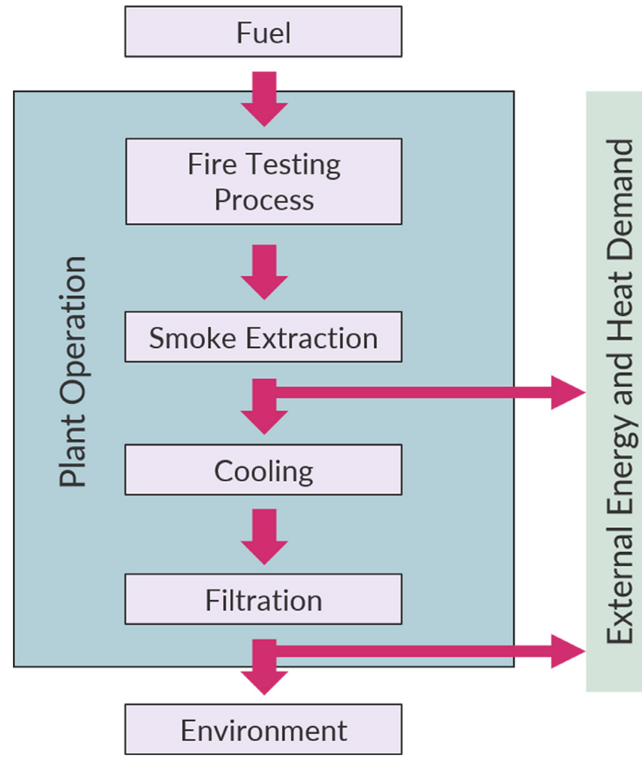

Fig. 1. Components within a cold abatement system with potential locations for heat recovery.

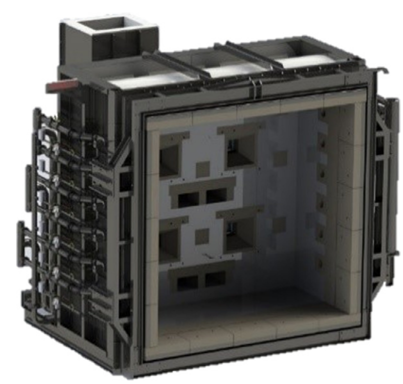

Fig. 2. A typical wall furnace [11].

When these particles are deposited on a surface, it is known as soot where the size of each particle is approximately 2.5 microns [16]. According to the study reported by Hurley et al [17]., the process by which smoke becomes deposited on surfaces is complex and can be the result of a dominant physical mechanism or a combination of mechanisms which can include particle inertia, gravitational settling, Brownian diffusion, thermo diffusion and electrostatic precipitation. Krause et al [18]. conclude that soot will accumulate in areas such as turning vanes and coils more than less complex areas such as straight lengths of ducts within a ductwork system. As the soot will act as an insulating medium on the heat transfer surfaces, its rate of build-up leading to its thickness is key to determining the viability of heat recovery within the smoke [19], while soot's thermal conductivity is about 0.07 W/m•K [20].

The rate of soot build-up on a water-cooled surface had been investigated by Ciro et al [19]. in 2006 and Fig. 3 was produced for showing that the good agreement between measured and calculated soot layer thickness on the bottom half of the container. This indicates that there was a build-up of soot on a water-cooled surface, such as an air-to-water

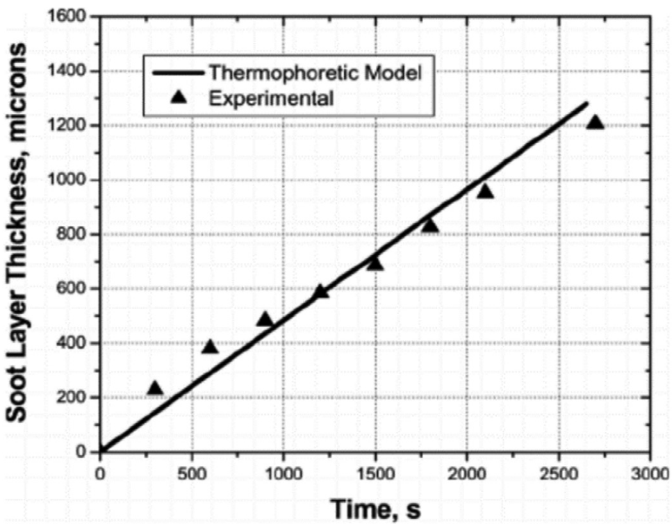

Fig. 3. Soot thickness over time – measured vs. calculated [19].

heat exchanger, of approximately 0.5 μm/s. However, this build-up was taken from 30 cm above a pool fire and therefore this would achieve the maximum soot deposit possible on the water-cooled surface. The heat exchanger for the furnace smoke extract system would be some distance away from the source of the fire. Therefore, a reduction in the rate of soot deposition on the heat exchanger can be expected. This is due to soot being deposited on the inside of the ductwork between the furnace and the heat exchanger. Additionally, the soot generated in the experiment by Ciro et al [19]. was as uniform as possible, whereas the soot produced by the furnace testing would not be uniform due to inconstancies within the subjects being tested (not all one material) and the changes in the subject's condition and composition over the length of the test. According to the literature review of Hakes et al [21]., some of the materials that could be tested are plasterboard, various types of bricks, windows and frames, various types of insulation, fire stopping material and building services components used to reduce fire spread.

Furthermore, studies show that the soot deposit on a heat exchanger would be lower than if it were directly above the source of the smoke, and with the close soot deposition being 0.5 μm/s, the assumed further away soot deposition could be 0.25 μm/s [22], which was adopted in case studies in this paper. However, this number can be refined with testing on the wall furnace's extract system if it were to be installed with a heat exchanger. A study by Mulholland et al [23]. suggests that the quantity of soot that was deposited on surfaces varied based on the difference in temperature between the smoke and the surface itself. It was approximately proportional to the ratio of the temperature difference to the inlet temperature.

In terms of the form of heat exchanger, a coil heat exchanger is commonly applied in various industrial processes, which can be categorised by the finned and unfinned tube coil heat exchangers. Both finned and unfinned tube coil heat exchangers work in a very similar way as it is the difference in their overall size when comparing two heat exchangers that have the same quantity of heat transfer surface area [24]. The unfinned tube coil heat exchanger would need to be significantly larger than the finned tube coil heat exchanger, however, this increased size allowing for a greater distance between internal surfaces enabling cleaning of the heat exchanger to be more thorough [18]. Paz et al. reported [25] that the cleaning of the heat exchanger is crucial when the smoke would have to be performed after every test due to the quantity of soot that would build up on its surfaces. Smits et al [26]. revealed that soot can be cleaned through a mild biodegradable cleaning solution. However, another research found that soot can react with the coils and form a hard and crystallised material that requires sufficient force to remove [27]. This hard material is best removed with an alkaline cleaning solution and a pressure washer [18] and therefore sufficient spacing between all the sections of the heat exchanger are required to be able to clean it. The cleaning and maintenance strategy for a typical Electrostatic Precipitator's internal workings is once a week to once every three months depending on the degree of pollution [28]. It is concluded that the unfinned tube coil is the heat exchanger of choice for any areas of ductwork where there is smoke presence and the finned tube coil will be chosen where there is no smoke [24]. Hamid et al [29]. found that there was an impact on a heat exchanger after it was cleaned as mass was deposited which increased the pressure drop through the heat exchanger but decreased the heat exchange efficiency. However, this effect on the heat exchanger was ignored for this paper as it was assumed the soot covered heat exchangers to be cleaned with high pressure water only and therefore no residue was left.

In addition, there are many applications in building operations that could benefit from hot water being introduced into them. Elmegaard et al [30]. reported a study on a Low Temperature / Pressure Hot Water (LTHW / LPHW) system, which was used to heat buildings via radiators, trench heaters and heating coils within the ventilation ductwork. Studies have demonstrated the maximum water temperature required for an LTHW system is 85°C [31], but the temperature required could be lower at 45°C for applications such as underfloor heating [32]. Further, the hot water for domestic water systems must be provided to the outlets at above 50°C to make sure that there is no legionella present within the water; At these temperatures legionella cannot survive and therefore is safe to consume [33].

Should the heat generated by the heat exchanger be in excess of what could be used locally within the building, then there is a potential for it to feed into a district heating network such as the large one found in the city of Copenhagen [34]. If the potential heat energy is to be converted into electricity, a steam turbine would be required. However, relevant studies found that such steam turbines typically require the steam to be at a higher temperature above 500°C [35]. At this point, there is no opportunity to generate electricity from the steam generated within the heat exchanger due to the smoke's starting temperature being lower than 300°C [36]. Moreover, Barth et al [37]. found that there was a risk that any heat exchangers located within the path of smoke could be subject to corrosion. In recent years, Erguvan et al [38]. revealed that with enough time and exposure to the smoke, the heat exchangers would have less surface area available and would therefore lose some efficiency. Earlier, Bird [39] concluded that using a suitable material like copper as the heat exchanger could reduce the effect of corrosion. However, all of the previous studies provide limited information about the viability and actual performance of the heat recovery through the smoke extracting processes.

This paper investigated and explored the constraints for a concept in recovering the heat from a smoky environment such as the one found in the extract system of an apparatus to test the fire resistance properties of building materials, which is commonly used within the construction of new buildings. The potential to explore this topic emerged from discussions with a fire testing company in the United Kingdom regarding the design of a new set of furnaces for their expansion. There was some interest from the industry in exploring this concept, but a design team had ignored the idea since it had not been implemented elsewhere. The ignorance of the concept was not backed up by any prior experiences or studies, however it is recognised that there are only a few continuous smoke extract systems in the UK due to their uniqueness, ensuring that a bespoke design would be needed to harness energy potential from the furnaces.

2. Methodology

This study employed mathematical modelling to identify the range of potential energy recovery from the selected fire test system. According to BS EN 1363-1 [13], the resistance to fire test can be any length of time

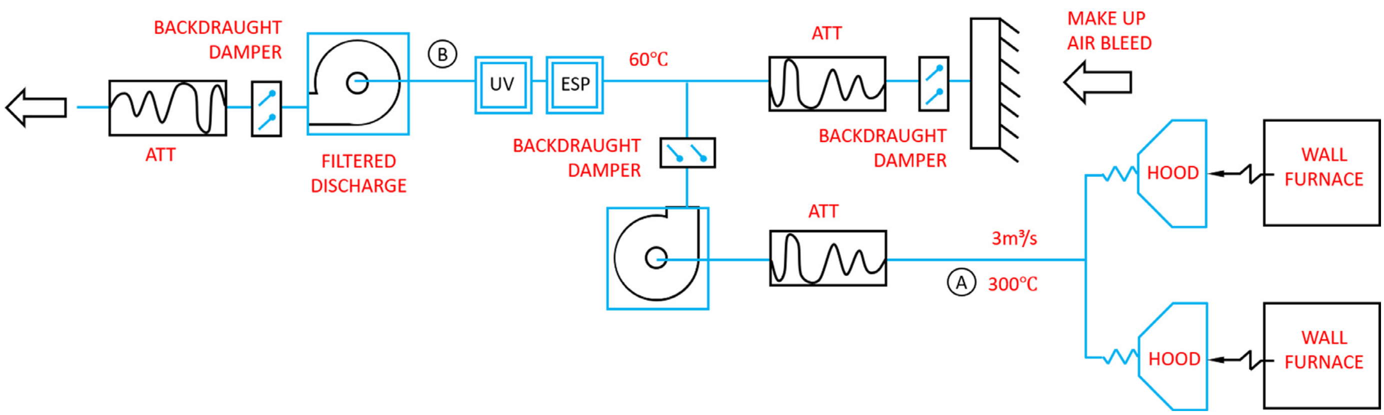

Fig. 4. Schematic diagram of the cold abatement extract system.

between 30 minutes and four hours. The test is stopped when either the required length of time is reached or when the test subject fails [13]. This paper presents the results for recovering heat from a 30-minute test, a one-hour test and a three-hour test to assess whether there is an optimal testing duration for recovery heat.

During a fire test, there are two abatement systems to remove the hot and harmful substances from the test area – the 'hot' and 'cold' abatement extract systems. The cold abatement system was the focus of this paper. A schematic diagram illustrating this process is set out in Fig. 4. The smoky air within the system is typically around 80°C, which is a combination of a smoke of 300°C from the furnace and the ambient air. To filter the smoke out of the air before it is exhausted to atmosphere, there are Electrostatic Precipitators (ESP) installed in the system. However, these can only operate up to 60°C [28] and therefore cooler outside air is mixed with the cold abatement to reduce it to acceptable temperatures. The proposed study in this paper was to consider which of the following three scenarios is the most viable:

1) Removing heat from 300°C smoky air if the furnace and extract system are in a closed loop system which doesn't allow any mixing of cooler air before a heat exchanger.
2) Recovering heat from 80°C smoky air after the 300°C smoke has been extracted with the room's ambient air forming the mixture of air.
3) Recovering heat from 60°C clean air after it has been cooled by the ambient air and the outside air.

In order to effectively assess the viability of obtaining some heat recovery from a fire testing smoke extract system, there was a requirement to test a number of different scenarios. There were two positions (detailed as positions A and B within Fig. 4) within the cold abatement system where mathematical models were produced. Scenarios 1 & 2 were located at position A and Scenario 3 was located at position B. The reason why these two positions had been chosen was due to the large temperature difference that could be achieved between them, and the only other difference would be the quantity of smoke within the air. It was assumed that position A with 300°C air that there would be the ability to exchange a greater quantity of heat compared to position B, the question being how much the accumulation of soot affected this. To re-iterate, a soot build-up rate of 0.25 μm/s was assumed in this study.

These scenarios were tested against three lengths of tests – 30 minutes, one hour and three hours. With these three different tests and operating times, the actual operation of the furnace included a mixture of all these test types, and therefore an average of the results was taken. This was because there might be different conclusions that could be drawn at the different test lengths between all three scenarios. For each test, the quantity of heat recovered was calculated at the start of a fire test when the heat exchangers were free of smoke. As the tests went on, the quantity of heat that could be recovered from the heat exchangers in the position A (as shown in Fig. 4) decreased as the thickness of soot deposited on the heat exchanger increased. Therefore, a series of calculations were required to demonstrate the rate of decrease in efficiency. Calculations for every 1 μm of soot that was deposited on the heat exchanger allowed for 2,700 calculations to take place over the maximum of a three-hour fire test.

2.1. Analytical modelling approach

A mathematical model, which, based upon validated relevant equations [40], was developed to determine the amount of heat transported as a result of a temperature change. The following equation has been used to calculate the quantity of energy that was released from the smoke as it passed over the heat exchangers:

$$Q = \dot{m} \cdot c_p \cdot \Delta T \tag{1}$$

To demonstrate the temperature changes throughout the heat exchange process, the following equation was used:

$$\dot{m}_1 \cdot c_{p1}(T_1 - T_2) = c \cdot \dot{m}_1 \cdot c_{p_2}(t_2 - t_1) \tag{2}$$

where c is the heat exchanger eficiency.

The equation to calculate how much energy can be transferred between two fluids through a heat exchanger is stated as:

$$Q = U \cdot A \cdot \Delta T_m \tag{3}$$

The Eq. (4), as follows, was implemented for calculating the log mean temperature from all of the observed temperatures within a heat exchanger:

$$\Delta T_m = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln\left(\frac{(T_1 - t_2)}{(T_2 - t_1)}\right)} \tag{4}$$

In position A within the cold abatement system, the soot attached itself to the heat exchanger's surfaces and therefore the system's heat transfer coefficient (U-value) within this calculation changed throughout the course of the resistance to fire test. Therefore, the following calculation was used to determine the U-value:

$$U = \frac{1}{R_{so} + R_1 + R_2 + \ldots + R_n + R_{si}} \tag{5}$$

however, within the calculations performed within this paper, the R_{si} and R_{so} were taken as 0 due to them having a negligible effect on the final results. The individual resistances for all the materials within the heat exchanger were calculated using the following formula:

$$R_T = \frac{k}{l} \tag{6}$$

2.2. Boundary conditions

The parameters that were required to understand the viability of incorporating a heat exchanger and energy generation from this system

Table 1
Parameters for the mathematical model of the system.

Parameter	Value
Smoke / Air density	1.18 kg/m^3 [41]
Smoke / Air specific heat capacity	1.04 kJ/kg•K [42]
Efficiency of the heat exchanger	100 %, ideal condition
Mass flowrate of the water	1 kg/s, normal condition
Water specific heat capacity	4.2 kJ/kg•K, normal condition
Heat exchanger tube wall thickness	1.25 mm [11]
Steel thermal conductivity	15.1 W/m•K, normal condition
Soot thermal conductivity	0.07 W/m•K, normal condition

are detailed below. In this study, the proposed heat exchanger was considered a mathematical item only, which was not tied to a particular type.

- The typical smoke density and temperature from a test
- The volumetric / mass flowrate of smoke through the extract system
- The volumetric / mass flowrate of the water through the heat exchanger
- The heating application and therefore what temperatures were required to be achieved by the hot water generation
- An average length of time in which a heat recovery system could be functional for including the hours of operation of the fire testing furnace
- Extract system maintenance routine after every test
- Technical specification of heat exchanger regarding its construction and therefore ease of access for cleaning. In addition to this, the total surface area that could be used for heat transfer between the smoke / air and the water
- The assumption that the heat exchanger be 100% clean before each test commences
- The general efficiency degradation of the heat exchanger
- The efficiency of the heat exchanger. For all calculations, it was assumed that the heat exchanger was 100% efficient and there were no losses into the local environment

There were some assumptions that had been made based on ideal or normal condition and literature. Therefore, there were many similarities within each scenario's initial parameters, and where appropriate, these were used to ensure a consistent approach. These assumptions are detailed in Table 1.

At the position A, Scenarios 1 & 2 were located where the smoke was at a temperature of 300°C and 80°C, respectively. The differences between these two tests were the way in which the hood had been designed over the furnace. Scenario 1 assumed that the hood was a closed system which only allowed the hot smoke to enter with minimal additional air from the space in which the furnace was located. As the temperature dropped for the smoke in this test was only 50°C down to 250°C, there was a need to provide mixing with cooler air, either from the local environment around the ductwork just after the heat exchanger or from outside air. This was so that the smoke reached the ESP at or below its maximum operating temperature of 60°C.

Scenario 2 assumed that the hood allowed for some ambient air from within the space to enter the extract system, this therefore reduced the temperature of the smoke as it reached the heat exchanger to 80°C. The temperature of the smoke was reduced to 60°C by the heat exchange process which was sufficient for the ESP to be able to clean. At position B, the smoke had been cleaned by the ESP filter, containing no contaminants, and had a maximum temperature of 60°C, as this was the maximum operational temperature for the ESP.

3. Results and discussion

Before the findings could be analysed and discussed, a few computations were completed. Using Eq. (2), the final water temperature, which was used for the heating application, was calculated. A summary of these calculations is shown in Table 2.

A calculation of the overall U-value for the heat exchanger and how this would be changed due to the soot built up on the heat exchange surfaces for the fire test was required. The thermal resistance of the steel tubes on the heat exchanger was a fixed value in all three testing scenarios and was calculated using Eq. (6) to be 0.00008278 m^2•K/W. For Scenarios 1 & 2, the quantity of soot on the heat exchanger built up over time and the thermal resistance also increased, which reduced the quantity of heat that could be transferred. These two thermal resistances were inserted into Eq. (5) to calculate the overall U-value of the heat exchanger over time. As there was no smoke presented within Scenario 3, there was no soot built up and therefore the U-value for the heat exchanger remained a constant of approximately 12080 W/m^2•K. Using the temperatures calculated in Table 2, the log mean temperatures were calculated for each scenario. These were 213.1°C, 21.2°C and 10.6°C for Scenarios 1, 2 and 3, respectively. The results to the quantity of heat that was transferred from the cold abatement system are shown in Fig. 5. The assumption was that the heat exchanger performed consistently throughout every test, having been cleaned, so that there was no soot remaining from a previous test. The flat line of Scenario 3 indicates that there was no degradation in the quantity of heat that could be recovered over the length of the test.

Upon analysing the data, the quantity of energy transferred halves after the quantity of soot on the heat exchange medium reached 6 μm for both Scenarios 1 & 2. This was a total time of 24 seconds. The quantity of energy reached a quarter of the original amount at 17 μm or 01:08 minutes. This was a rapid decline in efficiency as 75% of the potential heat gained from the heat exchanger was lost in the first 0.6% of the maximum three-hour test and 4% of the minimum 30-minute test. It is worthy of note that there was a significant pressure drop increase over the coils for the fans to overcome. The thickness of the pipes was increased by 2.7 mm over three hours, which reduced the gaps between the pipes of the heat exchanger by 5.4 mm and significantly impacted the performance of the fan.

From the graph in Fig. 5, it is clear to see that there was a major loss in efficiency for Scenario 1 & 2 where the soot accumulated on the heat exchanger. The lack of heat that can be recovered from Scenario 2, which indicates that this arrangement of recovering heat from the pre-filtered smoke when the ambient air was drawn in through the hood above the fire test was not viable. In comparison, Scenario 3 had the same quantity of heat being recovered at the start but remaining constant throughout the remainder of the 30 minute and three-hour tests. Scenario 1 might have the greatest quantity of heat recovered initially, however due to the large rate of drop off in efficiency incurred, over the 30 minute and three-hour tests, it was less efficient than Scenario 3. It reached the same level of heat recovery as test three when the soot reached 52 μm thick or at 03:38 minutes into the test. Purely based on the quantity of heat that could be recovered, Scenario 3 was the most viable option.

Fig. 5 also shows the overall quantity of heat that was recovered throughout the duration of the test. Scenario 1 initially recovered more heat than Scenario 3 up until 14 minutes into the test, at which point the efficiency of Scenario 1's heat exchanger becomes worse than Scenario 3's, despite the large difference in temperature. A factor worth noting with these results is that the amount of smoke in the cold abatement extract system remained constant throughout the test. This will not be the case in a real test as the subject may not give off any smoke at the start of the test. This would mean that there was a lot of hot air that wasn't too polluted when going through the heat exchanger in position A, and therefore the heat excahnger was very efficient as it would not have any soot deposited on it yet. Equally, the test subject may give off a disproportionately large quantity of smoke at the start of the test and coat the heat exchanger in position A with more soot than what had been calculated and reduce its efficiency.

Table 2
Testing temperatures for different scenarios.

Scenario	Smoke /Air initial temperature [°C]	Smoke /Air final temperature [°C]	Water initial temperature [°C]	Water final temperature [°C]
1	300	250	40	83.8
2	80	60	40	57.5
3	60	50	40	48.8

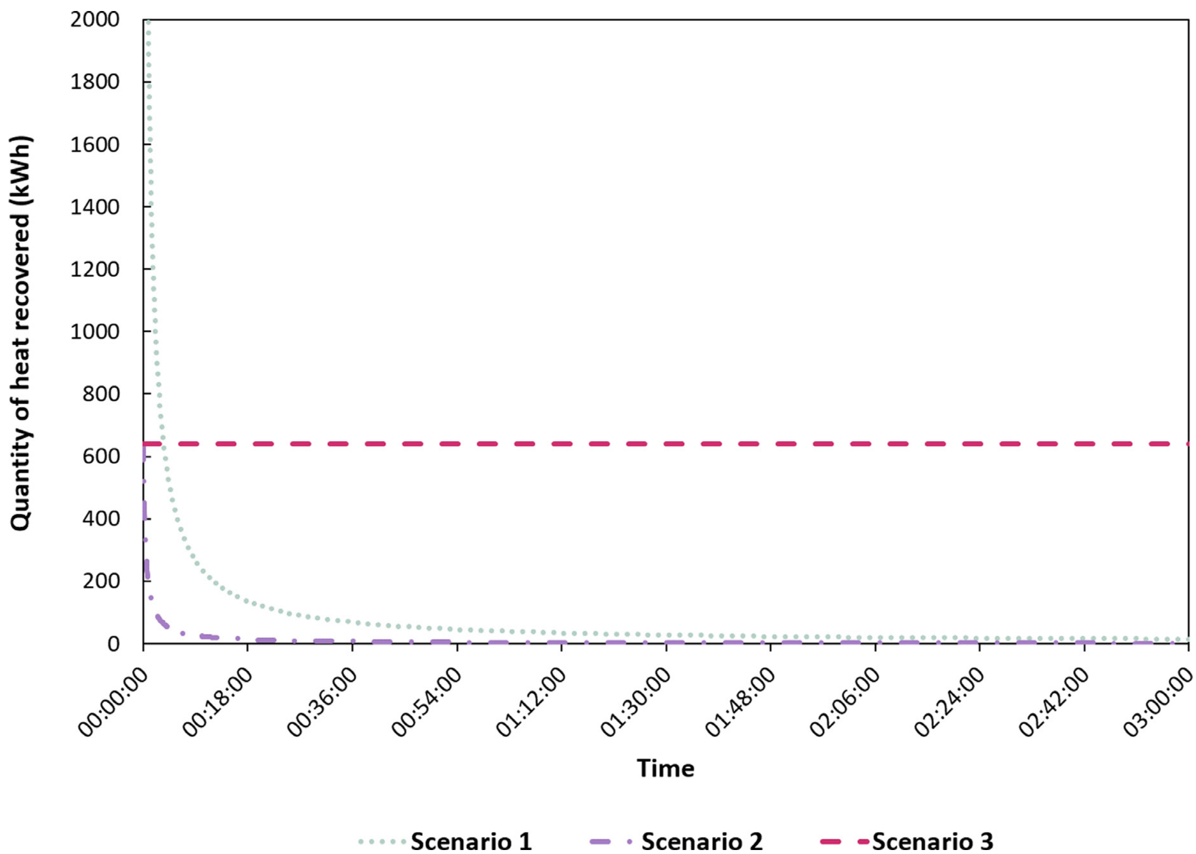

Fig. 5. Quantity of heat recovered over three hours.

From the mathematical model detailed in Section 2.1, the average amount of energy transferred from the smoke for each scenario was calculated for the three duration fire tests. This is detailed in Fig. 6 and when scaled-up to the test duration, this gives the total quantity of heat that was transferred over the duration of the tests which is detailed in Fig. 7.

It is clear to see that in Scenario 2, where the heat exchanger was within the smoky section of the cold abatement extract system at position A, it was not viable whatsoever. Scenario 2 was significantly worse than Scenarios 1 & 3, while Scenario 3 performed the best. There was a slow decline in the average energy that could be transferred within Scenario 1 but, when the total quantity of energy was calculated, it remained largely constant. This was due to the quantity of the transferred heat did not change significantly after the initially rapid decline during the test.

3.1. Further comparison and sensitivity analysis

A further discussion was carried out in this section to see how viable the heat recovery would be with some changes to the initial assumptions.

The original assumption was that soot deposited itself on the heat exchanger in position A, at a rate of 0.25 μm/s. If this value was 1/8 in size at 0.031 μm/s, then the results to this model were vastly different as demonstrated in Fig. 8. Both Scenario 1 & 2 show that their total energy transferred has increased when compared to that of Fig. 7 but, Scenario 2 was still not as efficient as Scenario 3. Where in the original conditions, the time at which Scenario 1 & 3 were the same was at 14 minutes, and with the more favourable conditions, they became the same at 1:55 hours. The rate at which soot deposited on Scenario 1's heat exchanger would have to be 0.021 μm/s or 1/12 of the original assumption, to make it just as efficient as Scenario 3 over the full three-hour test.

This result indicates that the heat exchanger in position A would be more viable than the heat exchanger in position B for tests shorter than 1:55 hours. However, this was with the assumption that the heat exchanger was cleaned after every test to remove all soot from all surfaces. This would add additional time and cost to each test which has the potential to outweigh its benefits for the shorter duration tests. This factor may make Scenario 1 less favourable than Scenario 3.

In terms of total energy recovered as shown in Fig. 9, Scenario 1 would perform the best for both the 30 and 60 minutes tests if the soot build-up rate was reduced at 0.031 μm/s. However, for the 180 minutes test, Scenario 3 would achieve the highest amount of total energy

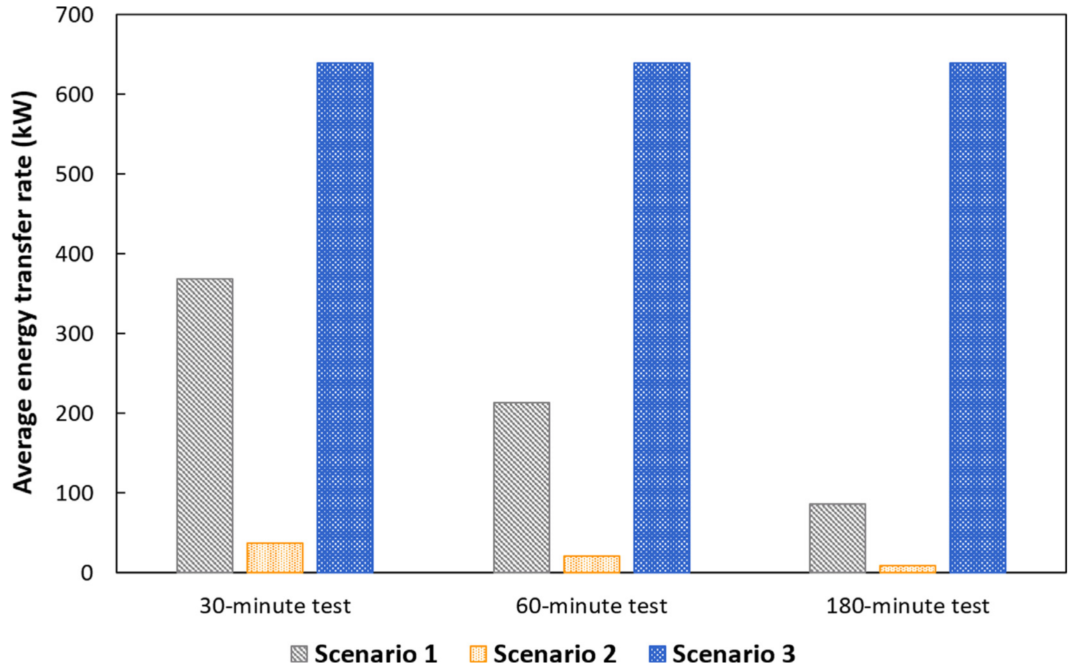

Fig. 6. Average energy transferred within each test scenario.

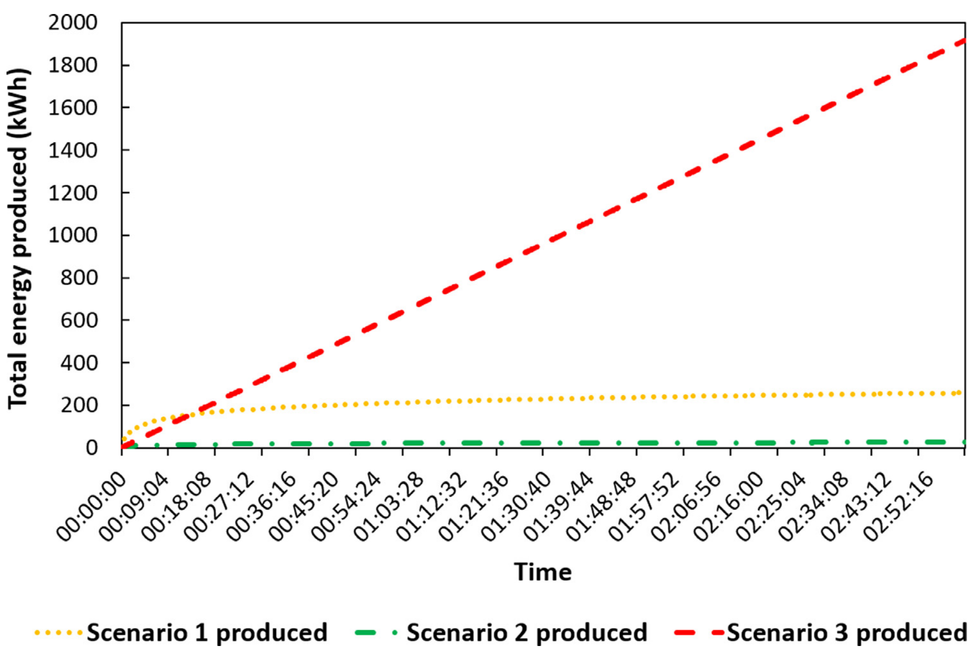

Fig. 7. Total energy transferred within each test scenario.

recovery without the change of the initial rate (i.e., 0.25 μm/s) for soot build-up.

4. Conclusion

This study focused on heat recovery of hot smoke through the fire testing wall furnace using the cold abatement extract system. It is found that depending on where a heat exchanger is positioned within the fire testing furnaces' smoke extract system, there is a different quantity of energy that can be transferred from the smoke or air to water. Among the three fire test scenarios, Scenario 1 had the highest quantity of heat that could be recovered at 184.1 kW, which is sufficient energy to heat 1 kg/s of 40°C water up to 83.8°C. Scenario 2 had 73.6 kW of energy that could be recovered, which would raise the temperature of 1kg/s of 40°C water to 57.5°C. Scenario 3 had the lowest amount of heat that could be recovered at 36.8 kW sufficient to raise the temperature of 1kg/s of water from 40°C to 48.8°C. At the start of the fire tests, Scenario 1 was the most viable option.

This did not take account of the fact that soot was deposited on the heat exchanger in Scenarios 1 & 2. It is found that the soot acted as an insulator and reduced the quantity of heat that could be recovered from the smoke, significantly reducing the efficiency of the heat recovery. The soot insulated the heat exchanger to such an extent that Scenario 1 reached the heat transfer levels of Scenario 3 within the first 3:28 minutes of the test, and Scenario 2 reached Scenario 3's levels almost immediately. This was mainly attributable to the heat exchanger's surface area within Scenarios 1 & 2 being half as much as Scenario 3. Even with Scenario 1's significantly higher starting transfer rate, it did not

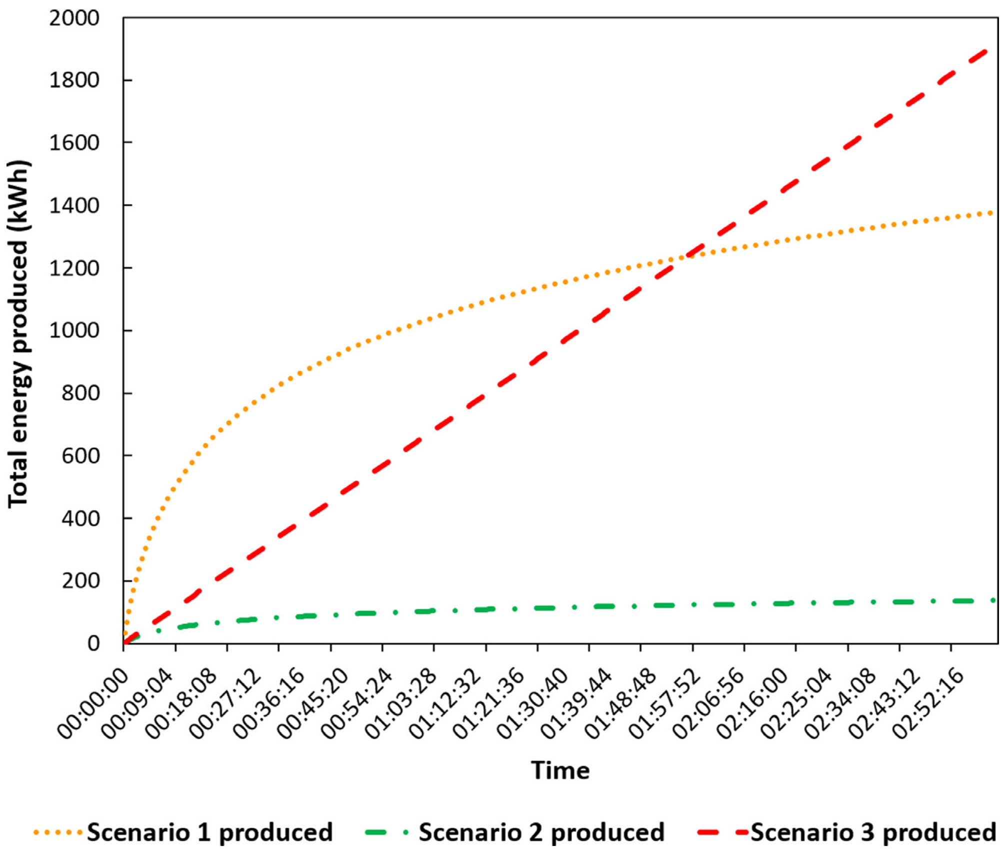

Fig. 8. Total energy transferred within each test scenario with less soot.

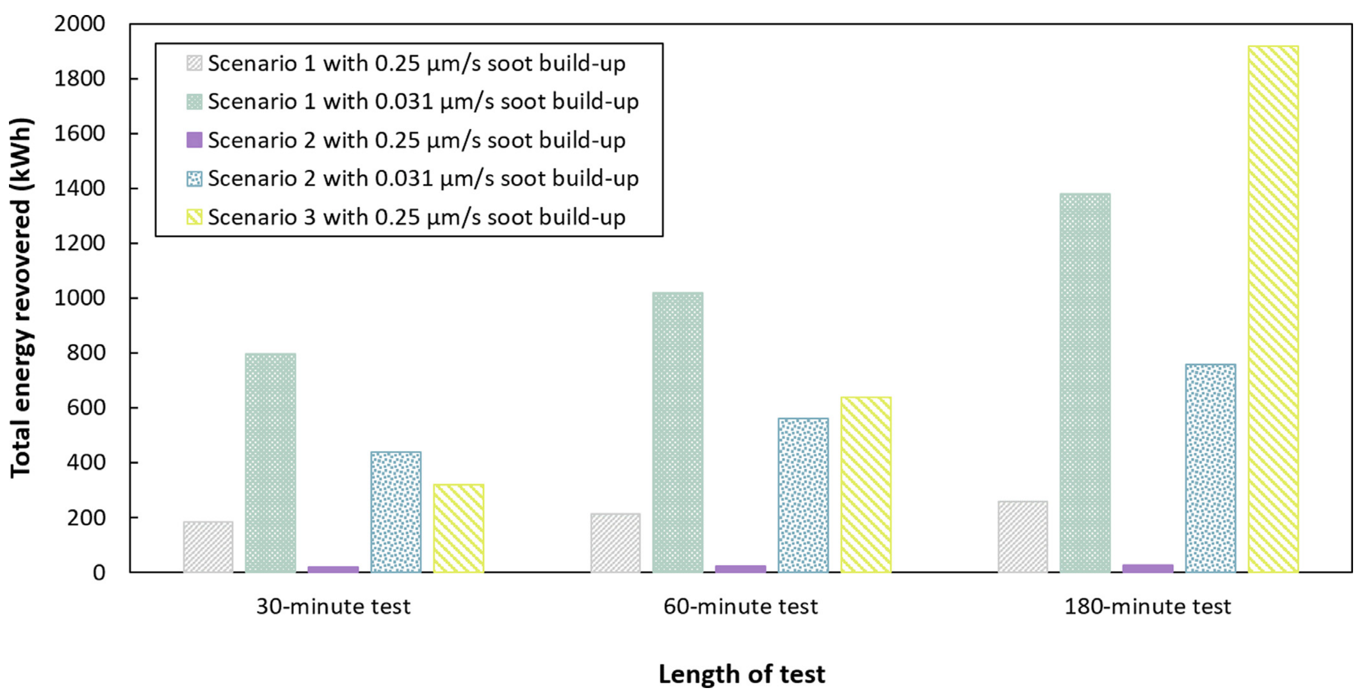

Fig. 9. Total energy recovered for each test scenario with different soot build-up.

achieve the same efficiency as Scenario 3's over the shortest 30-minute fire test. These scenarios were equal in their efficiency at 14:30 minutes, after which, Scenario 3 was more efficient. Even if Scenario 1 was more efficient over 30 minutes than Scenario 3, it would still need cleaning after the test whereas Scenario 3's heat exchanger was ready to run again as soon as the Electrostatic Precipitator had been prepared. On the other hand, the smoke with lower temperature was more efficient in recovering heat than that of higher temperature.

In summary, Scenario 3 was the most cost-effective solution too as it had significantly lower costs to maintain than Scenarios 1 & 2 where the heat exchanger was at position A. There was no day-to-day maintenance cost associated with Scenario 3 as it was positioned in clean air and therefore there would be no build-up of insulating materials on its heat exchange surfaces that would otherwise need to be cleaned off. This study reveals that having clean air was more important than higher temperature in the cold abatement system for heat recovery. In undertaking a sensitivity analysis on Scenario 3, there was a significant margin for the parameters to change for the better in Scenarios 1 & 2 and for Scenario 3 to still be more viable. The principal, that it does not need to be cleaned of soot after every fire test, means that this method of heat recovery would be the most viable out of the three scenarios. Fundamentally, a lower soot build-up rate and a longer fire test would perform the best in heat recovery for the wall furnace.

5. Future research

It would be interesting to consider that whether finned tube coil heat exchangers will be viable if there is a reduced rate at which soot deposits itself on the heat exchangers surfaces. The increased surface area may make the heat exchanger more efficient for its overall size and therefore the total quantity of heat will increase. It could increase enough and eventually level out and be the same as Scenario 3 after more than three hours of testing, after which it will need to be cleaned of all soot to bring its efficiency back. Based on the sensitivity analysis, there might be a good viability as to implementing the finned tube coil heat exchanger within the cold abatement extract system at position B. Further work should be undertaken to test this theory in a real-world environment. In order to do this, the company who will be testing the theory will do their own calculations based on those included within the mathematical model as they will be able to use more accurate data as per their existing fire testing furnace's smoke extract system.

Further, it would also be interesting to investigate which materials could be used within a finned tube coil heat exchanger that is placed in position A, that are more resistant to the deposition of soot. If the rate of soot deposition on the heat exchanger surface is less, then there will be a significant increase in the efficiency and therefore it will become more viable to use. One consideration would be to put the heat exchanger after a series of bends within the ductwork to allow more time for the soot to settle on the internals of the duct before reaching the heat exchanger. Other points of investigation would be into a method of removing the smoke out of the air without reducing the temperature significantly like the Electrostatic Precipitators did. If this is achieved, it would allow for a significant quantity of energy to be recovered from the cold abatement system.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Liam Hancox: Methodology, Formal analysis, Writing – original draft. **Siliang Yang:** Methodology, Supervision, Writing – review & editing.

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