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Characterisation of the steady state tube furnace (ISO TS 19700) for fire toxicity assessment

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ABSTRACT

The steady state tube furnace (Purser furnace, ISO TS 19700) has been developed specifically to replicate the generation of toxic products from real fires under different fire conditions on a bench-scale. Steady state burning is achieved by driving the sample into a furnace of increasing heat flux at a fixed rate and recording the product yields over a steady state period in the middle of the run. The furnace, sample, and effluent dilution chamber temperature profiles are presented to characterise the conditions in the apparatus. The distribution of smoke in the mixing chamber has been investigated to demonstrate the efficiency of mixing in the effluent dilution chamber. The heat flux applied to the sample at various points through the furnace has been measured, showing that conditions vary from those typical of pre-flaming to fully developed fires. An initial investigation of the repeatability and interlaboratory reproducibility has been undertaken, showing acceptable low levels of uncertainty in the toxic product yields.

1. Introduction

The majority of fire deaths are caused by inhalation of toxic gases, such as carbon monoxide, hydrogen cyanide and other products of incomplete combustion [1]. Different materials produce different toxic gases and the widespread use of polymers has increased the toxic hazard from fire. Flame retarded polymers, once ignited, may change the fire environment dramatically [2]. A major difficulty of predicting fire hazards is related to reliable prediction of toxic product yields that are strongly dependant on both material and fire conditions. The ultimate solution is to run large-scale experiments, but the variety of fire scenarios, the cost and set-up time needed are often prohibitive. Fire hazard is a combination of flammability and fire smoke toxicity. While flammability has been extensively studied, fire smoke toxicity is difficult to replicate on a bench-scale, and tends to have been somewhat neglected. This illustrates the need to develop equipment capable of replicating real fires in order to provide data on fire toxicity to inform building and other regulators concerned with fire safety.

Most bench-scale fire models can only replicate the early stages of fire development, using small samples under open ventilation. However, the steady state tube furnace is capable of replicating each fire stage, from oxidative pyrolysis and well-ventilated flaming, right through to under-ventilated flaming, which is most difficult to replicate on a small scale, but the stage which causes most fire toxicity deaths.

The steady state tube furnace (BS 7990 [3] and ISO TS 19700 [4]) is both a standard test method and a research tool that can provide building engineers and designers with valuable data related to fire hazard. The significant advantage of the apparatus over other techniques is its capability to replicate the whole range of fire conditions.

Extensive research, reviewed by Pitts [5], on prediction of carbon monoxide evolution from flames of simple hydrocarbons, has shown the importance of the equivalence ratio φ (Eq. (1)).

$$\phi = \frac{\text{actual fuel/air ratio}}{\text{stoichiometric fuel/air ratio}} \quad (1)$$

Typically, for well-ventilated fires φ is less than 0.7, while for fuel-rich (vitiated) combustion φ is greater than 1.5. In a fully developed fire, with low ventilation, φ can be as large as 5. For many hydrocarbon polymers, the CO yield increases rapidly with increase in φ, and is almost independent of polymer [6]. In the steady tube furnace the ventilation can be characterised in terms of the equivalence ratio, based on the oxygen requirement for "stoichiometric" combustion to CO_2 and water.

In order to understand the behaviour of the tube furnace, and its sensitivity to different experimental parameters, it was necessary to characterise the apparatus in terms of temperature profiles, the

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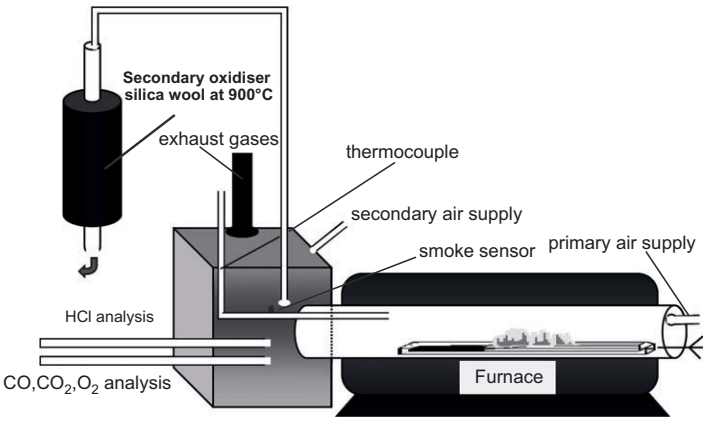

Fig. 1. The Purser furnace.

mixing inside the main parts of the apparatus, repeatability and reproducibility.

The steady state tube furnace (Purser furnace) [7,8] is a bench-scale test apparatus consisting of a tube furnace through which a sample is driven at a fixed rate, while being supplied with a fixed flow of primary air in order to replicate different ventilation conditions (Fig. 1). By control of the sample feed rate, the temperature inside the furnace, and the airflow rate, different fire stages can be replicated, so the yields for oxidative pyrolysis (smouldering), well-ventilated and small and fully developed under-ventilated flaming can be obtained separately [9]. The effluent from the tube is made up to 50 L min^{-1} with secondary air, by dilution within the effluent dilution chamber. By fixing the fuel and primary air feed rates, the equivalence ratio can be controlled. An early version of this apparatus appeared as the IEC 60695-7-50 standard [10], which defines extremes of under- and over-ventilation, by volume of air per unit mass of sample (e.g. well-ventilated used 22.6 L min^{-1} while under-ventilated used 2.6 L min^{-1}). BS 7990 and ISO TS 19700 use the more sophisticated equivalence ratio approach, where the oxygen requirement is determined using $\varphi = 0.7$ for well-ventilated flaming and twice the stoichiometric fuel/air ratio ($\varphi = 2.0$) for under-ventilated conditions.

As the sample is driven into the furnace, under an increasing applied heat flux, combustion is forced, even under reduced ventilation. After ignition occurs, the flame will stabilise in a part of the furnace corresponding to the pilot ignition temperature of the sample. The toxic product yield data is taken over the steady period of the run, when the burning behaviour has stabilised after ignition. A paramagnetic oxygen analyser, NDIR CO and CO_2 analysers are used to quantify the fire effluents, corroborated by CO and O_2 electrochemical sensors.

A secondary oxidiser containing quartz wool at 900 °C is used to fully oxidise a portion of the diluted fire effluent. The difference between CO_2 concentrations from the effluent dilution chamber and secondary oxidiser gives a measure of the products of incomplete combustion, such as CO, hydrocarbons etc. Oxygen concentration from the secondary oxidiser may also be measured to obtain φ for commercial products or other materials of unknown composition.

2. Experimental characterisation

The fire condition is dependant on the radiant flux, or temperature. Temperature profiles between the quartz furnace tube and the furnace liner were measured. Temperature profiles of the boat within the furnace tube, with and without polymer as it travels into the furnace, are reported for different fire conditions. In addition a vertical temperature profile inside the effluent dilution chamber shows the flow of effluent gases. In order to relate the steady state tube furnace measurements to different fire tests and scenarios, it is necessary to measure the radiant heat flux in the sample boat for different temperatures; this was achieved using a slug calorimeter (a small solid cylinder of copper containing a thermocouple in its centre). Radiant heat flux measurements were undertaken for 350, 650 and 825 °C. The cooling effect of primary air on temperature inside the tube has been shown to be significant for higher air flows.

Experimental repeatability is important in assessing the reliability, and to estimate the uncertainty in the measurements. Replicate runs were performed to determine the repeatability using different materials and different fire scenarios. The ability to reproduce two fire stages for polypropylene is compared to the defined fire stages of ISO 19706 [11].

2.1. Temperature profiles between the furnace tube and the quartz combustion tube

The flow of air through a cylindrical tube will either be laminar, at low velocity or turbulent, at higher velocity. If an empty cylindrical furnace tube is considered, an empirical rule predicts that only airflows greater than 1000 L/min would flow so quickly through the tube that they give rise to a Reynolds number greater than 2300. This is the point when the flow would be expected to switch from laminar to turbulent. The airflows used in the tube furnace are much lower, not normally exceeding 25 L min^{-1}. However, the presence of the sample boat with a vertical end occupying approximately half of the furnace tube area would be expected to disrupt the laminar airflow of the primary air as it travels over the burning sample, particularly at higher air velocities. The temperature profiles outside the furnace tube (between the furnace lining and the quartz furnace tube) shown in Fig. 2 were measured when the furnace was set to 700 °C by inserting

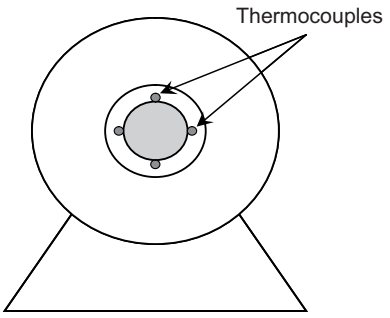

Fig. 2. Positions for measurement of temperature using four thermocouples.