Applied Thermal Engineering 125 (2017) 972–977

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Influence of depressurized environment on the fire behaviour in a dynamic pressure cabin

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HIGHLIGHTS

- Burning rate decreases linearly and is consistent with radiation modeling.
- Flame height increases first and then decreases slightly as pressure decreases.
- Regions of flame all elongate, in which temperature have different tendency.
- Fire behaviour still keep the trend before in the transition stage.

ARTICLE INFO

Article history:
Received 3 April 2017
Revised 19 June 2017
Accepted 11 July 2017
Available online 13 July 2017

Keywords:
Dynamic pressure
Depressurization rate
Pool fire
Fire behaviour

ABSTRACT

Aircraft cargo compartments usually undergo a dramatic pressure change during an emergency landing. Understanding fire behaviour in this dynamic-pressure environment is important for controlling aircraft fires. Pool fire experiments were conducted in a 3 m × 2 m × 4.65 m cabin to analyze fire behaviour in an environment with varying pressure. A pressure control system was used to reduce cabin pressure during the fire. N-heptane pool fires with diameters of 20 cm and 30 cm were tested under depressurization from 101 kPa to 24 kPa with depressurization rates of 148 Pa/s, 208 Pa/s, 261 Pa/s, and 304 Pa/s. Fire behaviour such as burning rate, flame height, and flame temperature were analyzed. The results revealed that as the pressure is reduced, the burning rate decreases, which agrees with radiation modeling. Flame height increases as a power function of pressure while the peak time is earlier than the end time of depressurization. Three regions of flame all elongate and flame temperature in each region shows different trends. Moreover, there is a delay for the fire behaviour to reach the next quasi-steady stage after the depressurization, which can be divided into the transition stage.

1. Introduction

With the rapid development of the aviation industry, the aircraft fires have become increasingly serious and thus deserve more attention [1–3]. According to the flight crew operating manual (FCOM) [4,5], an aircraft should be landed as quickly as possible in the event of fire during a flight. If there is no emergency landing option, the aircraft should climb an altitude of 20000 ft–25000 ft (6096 m–7020 m) altitude and equalize the compartment pressure with the exterior atmosphere to suppress the fire [6]. Implementing either of these measures will result in the compartment pressure changing dramatically. Therefore, the impact of a dynamic pressure environment on fire behaviour is worthy of study.

Previous studies of fire behaviour focus primarily on static pressure conditions at various altitudes, such as those in plateau and plain [7–9]. It's difficult to decrease pressure by climbing to higher altitude. Therefore, the low-pressure experimental environment is created in a specially designed enclosed tank or container [10–12]. The burning rate under low pressure atmosphere can be usually described by pressure modeling [13] and radiation modeling [14–16], which both take into account the ambient pressure and equivalent pool diameter. At a constant burning rate, flame temperature increases slightly under low pressure because of decreases in radiation heat loss and oxygen partial pressure [17,18]. Flame height is well represented by the unified formula with a modified correlation parameter reflecting air entrainment into flame presented in Hu, L. et al. [8]. And Tang, F., et al. revealed that the flame pulsation frequency of pool fire could be well characterized by a non-dimensional function of the Strouhal (St) and Froude (Fr) numbers [19–22].

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http://dx.doi.org/10.1016/j.applthermaleng.2017.07.088
1359-4311/

Nomenclature

D	pool fire diameter (m)
ΔH_g	latent heat of vaporization (kJ/kg)
ΔH_c	combustion heat (kJ/kg)
H_f	flame height (m)
L	mean bean length (m)
$\dot{m}$	burning rate (g/s)
$\dot{m}''$	burning rate per unit area (g/s·m^2)
p	ambient pressure (kPa)
$\dot{Q}$	total heat release rate (kW)
$\dot{Q}^*$	dimensionless heat release rate (kW)
$\dot{Q}_f$	heat feedback from the flame above (kW)
$\dot{Q}_l$	loss heat from fuel (kW)
$\dot{q}''_{rad}$	radiation heat (kW)
S	pool area (m^2)
T	flame temperature near fuel surface (°C)
z	flame characteristic length (m)
z	height above fuel surface (m)
k_1	thermal conductivity coefficient
k_2	thermal transfer coefficient
k_3	Stefan-Boltzmann constant
κ	effective absorption coefficient (m^{-1})
ρ	air density (kg/m^3)
c_p	air specific heat (kJ/kg·K)
p_0	initial normal pressure (kPa)
ε_f	flame emissivity
χ_r	radiation heat fraction

Subscripts

0	initial
f	flame
l	liquid surface
∞	ambient
cond	thermal conduction
conv	thermal convection
rad	thermal radiation

However, it is often not possible to control the interior pressure of these enclosed containers during the burn experiment. In recent years, the fire experiments with dynamic pressure control are receiving more attention. Jiusheng Yin [23] used a 3 m × 2 m × 2 m stainless steel chamber with pressures ranging from 101 kPa to 30 kPa to compare fire behaviour under three depressurization rates with static pressure. Qiuju Ma [24] performed n-heptane pool fire experiments with varying rates of pressure increase in an altitude chamber and discussed the effect of pressure change rate on burning rate and temperature. However, in general, there is still a significant lack of dynamic pressure experiments.

In this work, in order to explore fire behaviour in dynamic pressure environment more deeply, a pressure control system was installed in a 3 m × 2 m × 4.65 m cabin to accurately reproduce the low oxygen concentrations and dynamic pressure observed during aircraft climbing. The compartment pressure was decreased from 101 kPa to 24 kPa (sea level to 30,000 ft) at depressurization rates of 148 Pa/s, 208 Pa/s, 261 Pa/s and 304 Pa/s. Stainless steel pans with diameters of 20 cm and 30 cm were used during n-heptane pool fire tests. Burning rate, flame height, flame temperature and radiation heat flux were analyzed to understand and parameterize changes in fire behaviour under depressurization.

2. Experimental apparatus and measurements

The volume of the cabin was about 27.9 m^3, as shown in Fig. 1. The pressure control system consisted of an air-inlet pipe, an air-outlet pipe, and a vacuum pump. The air-inlet pipe was located at the floor of the cabin, while the air-outlet pipe was designed at the top of cabin and was designed with a larger cross-sectional area. The pump flow rate of pump was controlled by a PID system to produce the designated pressure change in the cabin. Steel pans 20 cm and 30 cm in diameter, 15 cm in height and 2.5 mm in wall thickness were used as fuel containers. The fuel consisted of n-heptane with an industrial purity above 99%, which has a density of 0.684 g/ml, an ignition point of 223 °C and a combustion heat of 4806.6 kJ/mol. The initial fuel depth was about 2 cm to ensure sufficient combustion time for both pan sizes. 10 cm of cold water was placed beneath the n-heptane in an attempt to prevent the fuel from boiling and protect experimental equipments below. A high-precision electronic balance with an accuracy of 0.1 g and a sampling rate of 1 Hz was placed under the pan to weigh and record the n-heptane mass loss. To measure the flame temperature, an array of 18 K-type 1 mm metal-sheathed nickel cadmium thermocouples were arranged on the centre line of the pan with 0.05 m spacing and labelled as T1-T18 from bottom to top. The thermocouples has an accuracy of 1 °C, a measurement range of 0–1100 °C, and were each sheathed in a ceramic tube to prevent the influence of the outside environment. The ends of the thermocouples were left uncovered and located in the centre line.The complete set of these devices were placed in the centre of the cabin, and a high-resolution video acquisition system recording at 25 frames per second was placed outside the observation window to record the flame shape.

Before the pool fire ignition by an electronic ignition device, the pressure inside cabin was adjusted to 101 kPa and the ambient

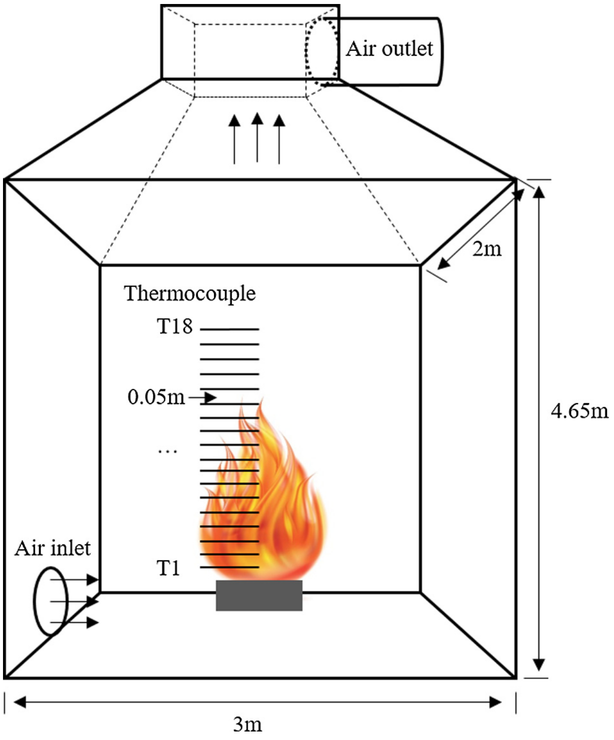

Fig. 1. Schematic of the experimental system in the dynamic pressure cabin.