RATES OF RADIATIVE AND CONVECTIVE HEAT TRANSFER IN AN AIRCRAFT CABIN

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ABSTRACT

Convective and radiative heat transfer rates to the inside surface of an aircraft cabin containing post-combustion gas from a 'pre-flashover fire' are calculated. In correlating the result with the likelihood of flashover, the need for consideration of the ease of thermal degradation of the combustible contents of the cabin is emphasised.

1. INTRODUCTION

A previous paper [1] dealt with calculation of radiative and convective heat transfer in a cabin of geometry 3 m cube, representing small retail outlets such as might be found at an airport terminal. Conditions assumed were that the cabin was uniformly occupied by post-combustion gas at 600^{o}C (873K) with the interior walls at 300K and, in the sense of thermal radiation, 'grey' with emissivity 0.85. The post-combustion gas was taken to be equimolar in the two participating gases - carbon dioxide and water. Under these conditions, the radiative rate of heat transfer was found to be 0.55 MW and the convective rate 0.21 MW, so that the combined rate was 0.8 MW. This is in the neighbourhood of 1 MW, the heat transfer rate usually regarded as signalling flashover.

In this follow-up work we extend the analysis to an aircraft interior. The author has spent some time ascertaining from the Internet the internal dimensions of several airliner types. Whilst the fuselage interior will have curvature and approximate to a cylinder, the actual cabin space occupied by passengers can be roughly cuboidal because of the roof, the floor and interior fittings at the walls. Accordingly, for calculation purposes the following *illustrative* values of the cabin interior of a narrow-bodied airliner have been used: width 3.5 m, height 2.5 m, length 25 m. A gas temperature of 500^{o}C (773K) will be incorporated, which is lower than in the previous example. This represents an envelope of gas associated with a localised fire at some position in the aircraft cabin whilst the remainder of the cabin is, before flashover, at a temperature in the neighbourhood 300K. A value of precisely 300K will be used as the wall temperature, as previously [1]. A partial pressure of 0.11 atm of each participating gas will also be carried over from the previous work. This signifies about 20% excess air. Rates of radiative and convective heat transfer for such an aircraft cabin uniformly occupied by post-combustion gas under these conditions will be determined.

2. DETAILED CALCULATIONS

2.1 Radiation

The path length L can be calculated from [2]:

L = 3.6V/A

where V is the volume of the gas and A the surface area of the enclosure. For a cuboid of width 3.5 m, height 2.5 m and length 25 m, this becomes:

L = 2.5 m

With a total pressure of participating gas of 0.22 atm, the product PL is calculated as:

PL = 0.55 atm.m

From the plot on page 146 of reference [3] or its equivalent elsewhere, the emissivity ε_G of the gas to one significant figure is 0.4.

Allowance has to be made for the fact that as well as emitting radiation the gas will also absorb radiation from the walls. For a *black* wall the relevant equation [3] is:

$$q = A_S\Omega\{\varepsilon_G T_G^4 - \alpha_G T_S^4\}$$

where q is the rate of radiation heat transfer (W), T_G is the gas temperature (K), T_S is the wall temperature (K), A_S is the surface area of the enclosure (m^2), Ω is the Stefan's constant (5.7×10^{-8} W $m^{-2}K^{-4}$), and α_G is the absorptivity of the gas.

If, as in this case, the surface is grey, the correction:

$q_{grey}/q_{black} = 0.5(\varepsilon_S + 1)$

where ε_S is the emissivity of the surface, applies In order to determine the absorptivity we have to have a value for ε'_G, the emissivity of the gas at the surface temperature (in this case 300K) and reduced beam length L^* given by:

$L^* = L(T_S/T_G)$

Giving to one place of decimals:

$PL^* = 0.2$ atm.m

The emissivities of the two participating gases individually can be determined and added together, making the necessary correction for mutual absorption. PL^* therefore becomes 0.10 atm.m for each gas. The individual gas emissivities to one significant figure are [4]:

$\varepsilon(CO_2) = 0.1$
$\varepsilon(H_2O) = 0.1$
$\Delta\varepsilon < 0.01$

where $\Delta\varepsilon$ is the necessary correction for mutual absorption and will be ignored in view of its very low value. Therefore:

$\varepsilon'_G = 0.2$

and also:

$\alpha_G = 0.2\{773/300\}^{0.55} = 0.34$

$q = A_S\Omega\{\varepsilon_G T_G^4 - \alpha_G T_S^4\}$

and an area of 317.5 m^2 applies. Substituting:

q = 2.6 MW

The above is for the case with black walls, whereas those in the situation under consideration are grey with an emissivity of 0.85, whereupon:

q_{grey} = **2.4 MW**

and this is the rate of heat transfer from gas to walls by radiation.

2.2 Convection

The previous work [1] involved a full analysis of the subject cabin – a 3 m cube – by treating it as four vertical surfaces and two horizontal surfaces and applying to each a suitable convection correlation incorporating the Nusselt, Prandtl and Grashof numbers (the product of the Grashof and Prandtl numbers being, of course, the Rayleigh number). Such an analysis is possible in the present case, but it is arguable that a more approximate treatment will suffice. The gas in the aircraft cabin will comprise nitrogen, carbon dioxide, water vapour and oxygen as we saw in the previous part. Nitrogen will strongly dominate, as in air, and to apply simplified correlations for air is most unlikely to lead to significant errors. Accordingly this route will be taken, and first we need the Rayleigh number, given by:

$$Ra = \frac{g\beta\Delta T x^3 Pr}{\nu^2}$$

where g is the gravitational acceleration (9.81 ms^{-2}), β is the coefficient of expansion = $1/T_f$ where T_f is the film temperature, ΔT is the temperature difference between wall and gas, x is the characteristic dimension (see below), and ν is the kinematic viscosity (m^2s^{-1}).

Now the film temperature can be equated to the mean of the wall (300K) and gas (773K), giving a value for T_f of 537K. At this temperature [2] the kinematic viscosity of air is 4.27×10^{-5} m^2s^{-1} and the Prandtl number 0.680. In Table 1, for each of the four surfaces – two walls, a ceiling and a floor – the Rayleigh number and convection coefficient are calculated and also the convective heat transfer rate q, according to:

$q = hA\Delta T$

where h is the convection coefficient (W $m^{-2}K^{-1}$) and A is the surface area (m^2).

The total rate of convective heat transfer = **1.2 MW**. The sum of radiative and convective rates of heat transfer from the gas to the cabin surface is therefore:

1.2 + 2.4 = **3.6 MW**

3. DISCUSSION

The obvious conclusion from these calculations is that if post-combustion gas at 500°C occupies part of an aircraft cabin interior because of a localised fire, flashover is to be expected. It is both a 'rule of thumb' and the prediction of the various models of flashover in illustrative calculations [5] that at about 1 MW flashover is likely to occur. The areas receiving heat by radiation and convection might conceivably have been underestimated by considering the floor, ceiling and walls only to the exclusion of interior fittings and the end walls. If this is so the calculated heat transfer rate errs on the low side.

Table 1: Summary of convection calculations

Surface	x	Ra	Equation for h [2]	h/ $Wm^{-2}K^{-1}$	A/m^2	q/MW
1st vertical wall, 2.5 m high, 25 m long.	Vertical height, 2.5 m.	5.0×10^{10}	$h = 1.31(\Delta T)^{1/3}$ applicable for Ra > 10^9	10	62.5	0.30
2nd vertical wall, all quantities exactly as for the first.	------------------	----------	-------------------	-----------	-- →	0.30
Floor, horizontal, 3.5 m width, 25 m length	area/perimeter = 1.5 m	1.1×10^{10}	$h = 0.59(\Delta T/x)^{1/4}$ applicable for Ra > 10^9 and heating from above.	2.5	87.5	0.10
Ceiling, horizontal, 3.5 m width, 25 m length.	area/perimeter = 1.5 m	1.1×10^{10}	$h = 1.52(\Delta T)^{1/3}$ applicable for Ra > 10^9 and heating from below.	12	87.5	0.50

Walton and Thomas *op. cit.* state:

> *Flashover is not a precise term, and several variations in definition can be found in the literature. Most have criteria based on the temperature at which the radiation from the hot gases in the compartment will ignite all of the combustible contents. Gas temperatures of 300 to 650°C have been associated with flashover, though temperatures of 500 to 600°C are more widely used. The ignition of unburnt fuel in the hot fire gases, the appearance of flames from openings in a compartment, or the ignition of all of the combustible contents may actually be different phenomena.*

and some conclusions relevant to the present work might be gleaned from this summary. Note first that in the above quotation flashover is correlated with temperature rather than with heat-release rate, and the same is true of some of the models for predicting flashover. A mechanistic aspect which is seldom if ever built into treatments of flashover but which is highly relevant is pyrolysis of flammable materials, both before and after flashover. The heat supplied during the pre-flashover period is used in decomposing flammable materials such as polymers and fabrics. Their flammable breakdown products are the primary fuel at flashover. This is the meaning of 'ignition of unburnt fuel in the hot fire gases' in the quotation above and, as stated there, this does not necessarily correspond with ignition of all the combustible contents.

The ease with which such flammable products are released depends upon the chemical nature of materials used in aircraft interiors, for example as seat coverings, carpets and wall panels. A huge amount of ongoing R&D is focused on making such materials as resistant as possible to thermal breakdown. Clearly this is likely to be more critical in an aircraft cabin than, for example, in a hotel lounge. If the fire load consists largely materials particularly resistant to thermal breakdown, this might call for a reconsideration of criteria for flashover in heat release or temperature terms. Without supplementary knowledge of the thermal degradation characteristics of whatever materials the aircraft cabin happens to contain, a conclusion that the total heat release rate calculated in the preceding section would unquestionably lead to flashover cannot necessarily be supported. The introduction of pyrolysis kinetics for various materials used in furnishings and floor coverings might be a helpful, though certainly not straightforward, extension of existing treatments of criteria for flashover.

4. CONCLUSIONS

The cabin of a narrow-bodied aircraft containing post-combustion gas at 500°C would experience heat transfer at a total rate of about 3.6 MW, two thirds of it due to radiation. Calculations using only well established principles in heat transfer have confirmed this. The inevitability of flashover is an obvious conclusion, but the need for further knowledge of the interplay of combustion, heat transfer and pyrolysis of unburnt fuel would be required for such a conclusion to be unequivocal. Perhaps a suitable start would be an investigation of any possible correlation of the temperature or heat-release rate for flashover and the simple fire load (weight of combustible material per unit area) of the enclosure.

REFERENCES

1. J.C. Jones, “Rates of radiative and convective heat transfer in a cabin fire”, Journal of Fire Sciences, Vol. 17, pp. 103-110 (1999).
2. J.P. Holman, Heat transfer, SI Metric Edition, McGraw-Hill, New York, USA (1989)
3. G.F. Hewitt, G.L. Shires and T.R. Bott, Process heat transfer, CRC Press, London, UK (1994).
4. F.P. Incropera and D.P. de Witt, Fundamentals of heat and mass transfer, 3rd edition Wiley, New York, USA (1990).
5. W.D. Walton and P.H. Thomas, “Estimating temperatures in compartment fires”, in SFPE Handbook of Fire Protection Engineering, 2nd edition, SFPE, Boston, Ma, USA (1995).