DEVELOPMENT OF THE LOW-TEMPERATURE FIRE EVENT MODELLING TECHNIQUE

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Abstract

A novel technique has been developed to model the behaviour of aircraft components under flame attack. This new technique is cheaper, faster and provides test data at higher resolution than the standard technique. The flow field of a certification-standard Propane-air burner is simulated at low temperature using a mixture of Helium and air with mixture ratio, flow rates and scale chosen to achieve correct matching of the relevant non-dimensional groups. The effects of mixing between the burner plume and the surrounding ambient air are also accounted for in the simulation. Heat transfer coefficient and gas temperature distributions, scaled from measurements in the low-temperature analogue plume, are input as boundary conditions to a numerical simulation of the fire test. The technique has been demonstrated by its ability to reproduce the measured component metal temperatures from an actual fire test. The design of the analogue burner has being refined to streamline the low temperature technique and further increase its accuracy.

1 Introduction

In a modern aero-engine highly flammable fuel, oil and hydraulic fluids are required for operation of the engine. While any leaks in the flow path of the engine will tend to be alleviated by the constant exchange of air, in regions such as the accessories zone within the nacelle, limited ventilation (often be a single ram air duct) can enable the dangerous build up of these combustibles.

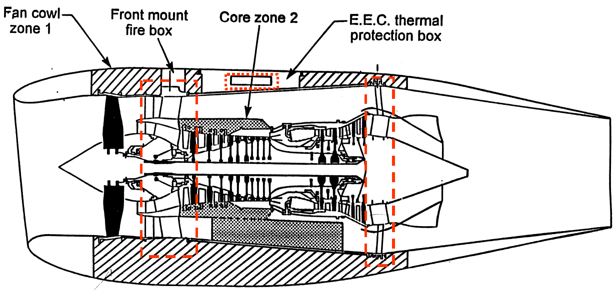

Figure 1. Typical engine fire zones in a small turbofan, critical components are indicated in red.

Regions, which combine combustibles, limited ventilation and spark sources, are designated as potential fire zones (Figure 1). If a fire where to break out in one of these regions it could possibly impinge on a number of components critical to the safe operation of the engine. Such components include the primary structural mounts and the electronic engine control box (Figure 1, Figure 2). While modern aircraft are designed to operate satisfactorily after an engine shutdown, damage to these critical components could result in catastrophic failure of the engine and even loss of the aircraft.

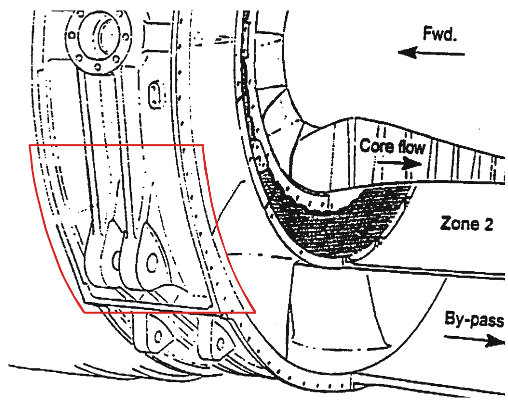

Figure 2. Detail of intercase mounting points.

2 Standard Fire-Certification Technique

Airworthiness regulations require that fire in and around aircraft engines does not hazard aircraft safety. The procedures for the testing of aircraft components in designated fire zones are specified in a variety of guidelines and standards issued by the certification authorities [1][2]. These procedures require a flight-worthy component to demonstrate its resistance to flame attack from a designated flame source. In the UK, the large Propane/air gas burner specified in ISO 2685 is commonly used to test large structural components (Figure 3). The burner is operated at close to stoichiometric conditions with a plume core temperature of approximately 2100K (Figure 4) [1][3].

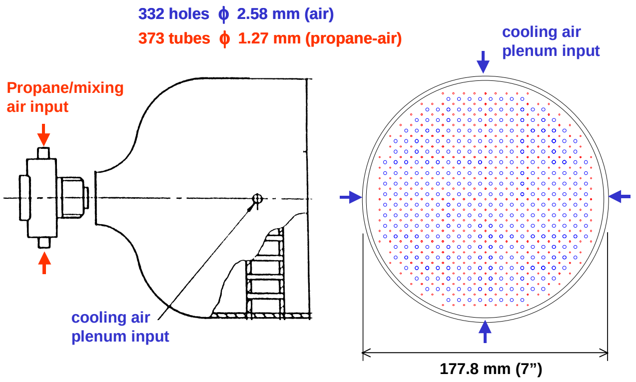

Figure 3. ISO standard propane-air burner [1].

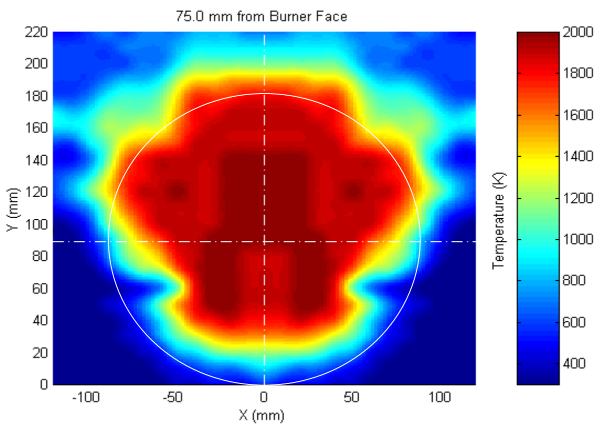

Figure 4. Transverse survey of measured gas temperatures in propane-air burner plume.

The methodology of the standard fire test technique is set out in Figure 5. Once the design has been finalized the flight-worthy component is manufactured. The relevant section of the component is instrumented with up to a dozen surface-mounted and imbedded thermocouples to monitor metal temperatures. In the case of the mount rings, ducting is attached to the rear of the components through which air is pumped to simulate the beneficial cooling effect of the bypass flow [4][5]. The component is then immersed in the flame from the standard burner for 15 minutes (Figure 6). Metal temperatures, interpolated from the discrete test measurements are input into a Finite Element Method (FEM) solver, as boundary conditions for operational stress calculations, to ascertain the fire-integrity of the component.

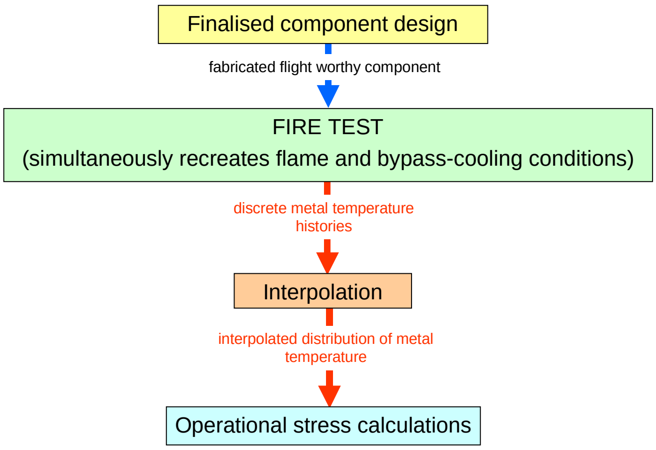

Figure 5. Methodology of standard fire test technique.

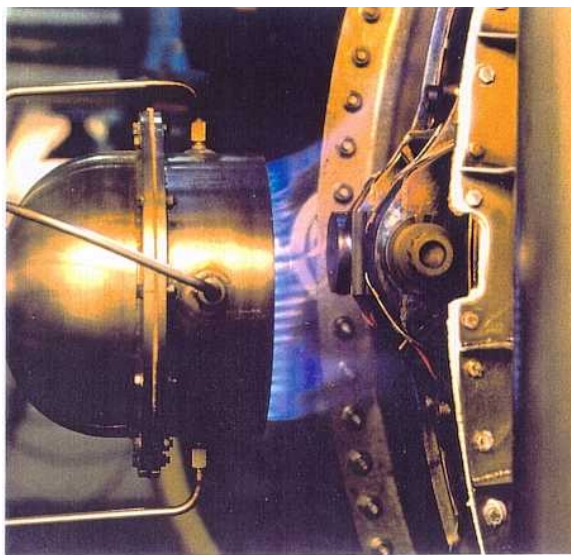

Figure 6. Flight-worthy intercase undergoing fire test in the flame of propane-air burner.

2.1 Limitations of the standard technique

The standard fire-certification technique has a number of limitations. The testing of the components is expensive and time consuming. The standards specify that fire tests must be performed on flight-worthy components. This requirement means that, due to the high cost, tests are normally only performed once the design has been finalised and the component has been manufactured. Thus, unless the component fails the test, there is no feed back of the test results to the design process other than as a body of experience. If the component does fail the test, a redesign is required and the whole fire-certification process must be repeated, resulting in a very costly delay in the engine programme. The resolution of the fire test is also limited to the distribution of thermocouples on the test component [3][4][5]. On geometrically complex components where metal temperature gradients are high, this can limit the accuracy of the test.

3 Low-Temperature Analogue Technique

3.1 Introduction

In a fire test, the heat transfer from the burner plume to the model is primarily via forced convection. Radiation from the nearly stoichiometric standard burner flame (equivalence ratio Φ = 1.096), is minimal [3][6][7][8]. For convective heat transfer, the heat flux (Q_c) to the component is governed by both the driving temperature difference between the wall (T_w) and the gas (T_{aw}) and the heat transfer coefficient (h) (eq. 1) [9].

$$Q_c = hA\left(T_{aw} - T_w\right) \qquad (1)$$

These two parameters are decoupled in the first order and can thus be modelled separately. The low-temperature analogue burner technique exploits the ability to separate the heat transfer parameters. The heat transfer coefficient is a function of the flow field. Thus if the flow field can be reproduced at low temperature, then the distribution of heat transfer coefficients across the component can be mapped at high resolution using thermochromic liquid crystal coatings on plastic models [3] (see §3.4). These coatings are applied as an aerosol paint and change colour at calibrated surface temperatures. A flow temperature of less than 100 °C is required to induce colour change in the liquid crystal coating across the model [10][11].

In the case of the mount rings, where convection of heat to the cold bypass flow also occurs, low temperature tests can again be used to map the heat transfer coefficients over the bypass surface. Distributions of T_{aw} are scaled from measurements made during the low temperature tests (see §3.5). The h distributions and T_{aw} distributions are input as boundary conditions into a finite element heat transfer analysis package (SC03) and combined with knowledge of the radiative behaviour of the component materials. The complete 15-minute fire test is then simulated numerically (Figure 7). The output of these calculations provides full metal temperature histories throughout the volume of the component. These metal temperatures can then be used directly in the operational stress calculations in SC03 to determine fire-integrity for certification.

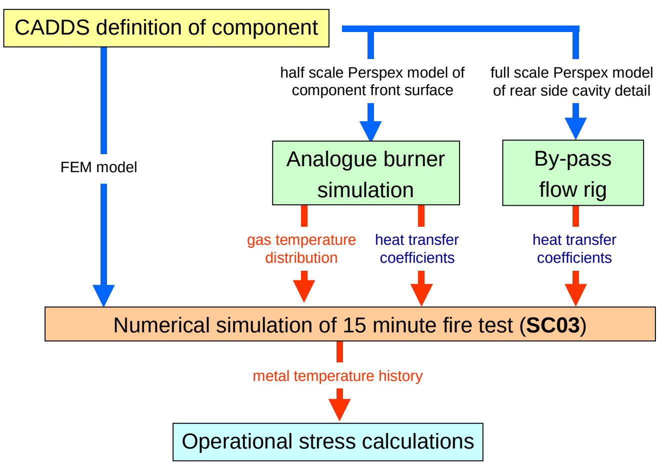

Figure 7. Methodolgy of low-temperature analogue technique.

3.2 Reproduction of burner flow field

As stated, the new technique requires that the burner flow field be reproduced at low temperature to permit the use of liquid crystal coated plastic models. The most noticeable property of the standard burner flow is the significant buoyancy of the flow due to the high flame temperature (Figure 6).

A dimensional analysis reveals the non-dimensional parameters which define the flow field and thus the heat transfer [3]. These are the Prandtl (Pr) and Reynolds (Re) numbers which govern the convective heat transfer through the viscous boundary layer. The Froude number (Fr), the density ratio between the plume and the ambient air (ρ_f/ρ_o), and the momentum flux ratio (J) at the burner exit, control the penetration of the plume into the surroundings and the subsequent buoyant shape of the plume.

$$Nu = f\left\{\mathrm{Pr}, \mathrm{Re}, \mathrm{Fr}, \frac{\rho_f}{\rho_o}, \mathrm{J}\right\} \tag{2}$$

The only way to reproduce the high density-ratio of the actual burner flame (≈ 7.5) at low temperature is to substitute a gas with low atomic weight. A mixture of Helium (96% by mass) and air is thus used to achieve the correct density ratio. The use of Helium (which has a substantially lower viscosity at 80 °C than the combustion products at 1827 °C) in turn requires testing at half scale to enable the simultaneous reproduction of Re and Fr. The use of half scale models is advantageous for a number of other reasons. The size of the models and the facility are reduced which makes the experiments more manageable for large components and reduces the cost and time of fabrication and instrumentation. Additionally the helium flow rates are halved, doubling the test duration available from a bottle, while the exit flow velocity is doubled, increasing the efficiency of the mesh heater used to heat the flow [12].

3.3 Design of the low-temperature burner

The layout of the low-temperature analogue burner facility is shown in Figure 8. Metered flows of air and He are mixed and fed into a plenum chamber of square cross section. The mixture is passed through a flow straightener and then across a fast response mesh-heater [13][14], a fine stainless steel mesh suspended across the flow passage which acts as a resistive heater when a current is passed through it. The heated mixture then passes through a square to round transition duct to the burner face. The burner face is not a half scale reproduction of the standard burner face. Rather the porosity of the burner face is selected to enable the reproduction of the momentum flux ratio (J) for the hot burner flow [3].

In the pilot low-temperature analogue burner facility, the faceplate was manufactured from transparent polycarbonate (to permit a camera to be placed upstream of the mesh heater in the plenum chamber) and had an appreciable time constant (~ 100 s). To obtain a step change in the gas temperature applied to the model, which is required for the transient thermal analysis, a shutter was introduced between the burner and the model, and only removed once the burner face temperature had equilibrated [3]. The removal of this shutter constituted the start of the thermal transient used in the heat transfer analysis.

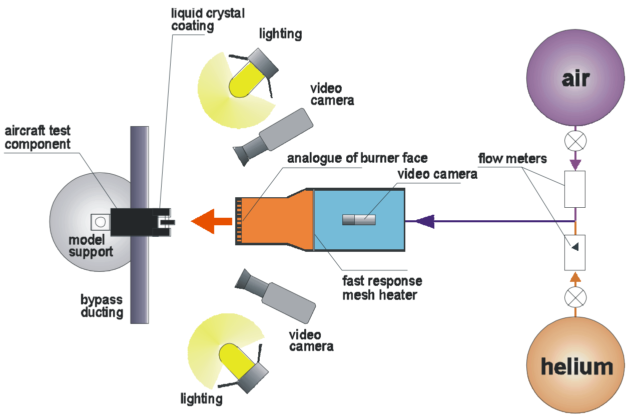

Figure 8. Layout of low-temperature analogue burner facility.

Video cameras and low-temperature fluorescent lights are positioned around the model to enable full visual coverage of the extents of the model surface.

3.4 Mapping the heat transfer coefficient distribution

The *transient liquid crystal* technique is used to determine the distribution of heat transfer coefficients across the surface of the model. This technique is widely used to measure heat transfer in low-temperature turbine blade experiments [10][11]. An accurate half-scale model of the component is fabricated from Perspex (a good insulator). This is painted black and then coated with a thin layer of encapsulated thermochromic liquid crystal material. The model is subject to a step change in gas temperature. Video histories of the resultant crystal colour change (Figure 9) are reduced to surface temperature histories and subsequently to distributions of heat transfer coefficient across the surface of the model, using an automated process.

Figure 9. Video camera view of intercase model showing liquid crystal colour change.

One dimensional semi-infinite heat transfer is assumed. At any point on the model surface h is a function only of the initial driving temperature difference ($T_{aw} - T_o$), the crystal change temperature (T_c), the material properties of the substrate (ρck) and the time at which the contour appears (t)

$$h = \frac{\beta\sqrt{\rho ck}}{\sqrt{t}} \qquad (3)$$

where $$\frac{T_c - T_o}{T_{aw} - T_o} = 1 - \exp\left(\beta^2\right)\mathrm{erfc}\left(\beta\right)$$

Care must be taken to select liquid crystals with colour change temperatures that are well placed between the initial surface temperature and the driving gas temperature.

The modelling technique described is designed to conserve the non-dimensional heat transfer coefficients between the hot flame and the cold simulation. The non-dimensional heat transfer coefficient is the Nusselt number which is a function of the scale (d) and the gas conductivity (k) as well as the heat transfer coefficient (h) [9].

$$\mathrm{Nu} = \frac{hd}{k} \qquad (4)$$

Assuming Nusselt number similarity for the low-temperature analogy and the flame condition, the heat transfer coefficients determined in the low-temperature tests must be scaled, for use in the numerical simulation at high temperature, by the ratio of the gas conductivities and the inverse ratio of the sizes.

$$h_{flame} = \left(\frac{k_{flame}}{k_{low\ temp}}\right)\left(\frac{d_{low\ temp}}{d_{flame}}\right)h_{low\ temp} \qquad (5)$$

This relationship assumes constant gas properties across the boundary layer. In the highly turbulent flow as the plume impinges on the model, heat is transferred across the boundary layer from the hot mixed bulk conditions to the relatively cold wall. The extreme temperature difference between the flow and the wall will result in significant variation of the gas properties across the laminar sublayer. This variation must be accounted for in the scaling of the experimental heat transfer coefficients [3]. A typical distribution of heat transfer coefficients across a component, scaled to fire test conditions, is shown in Figure 10.

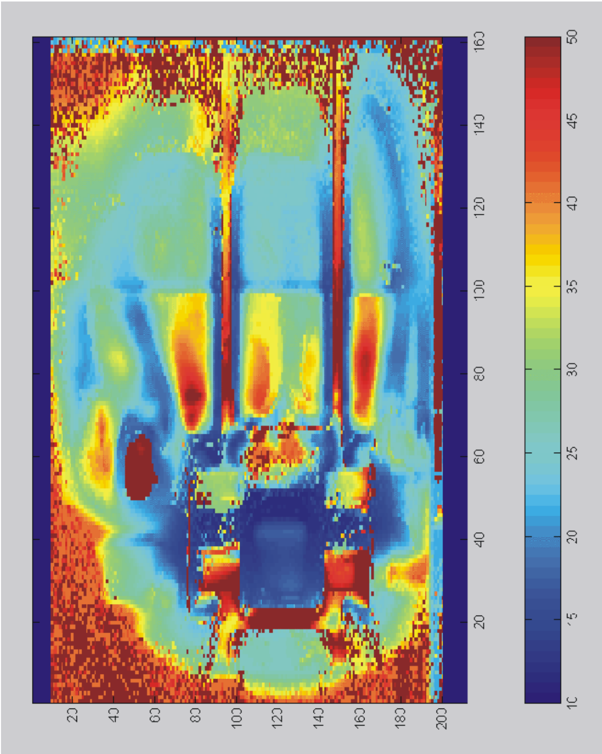

Figure 10. Distribution of heat transfer coefficient *h* ($W.m^{-2}.K^{-1}$) across the intercase.

The heat transfer coefficient distributions, together with the adiabatic wall temperature distributions, are applied as boundary conditions to the FEM model of the component for thermal analysis (Figure 11).

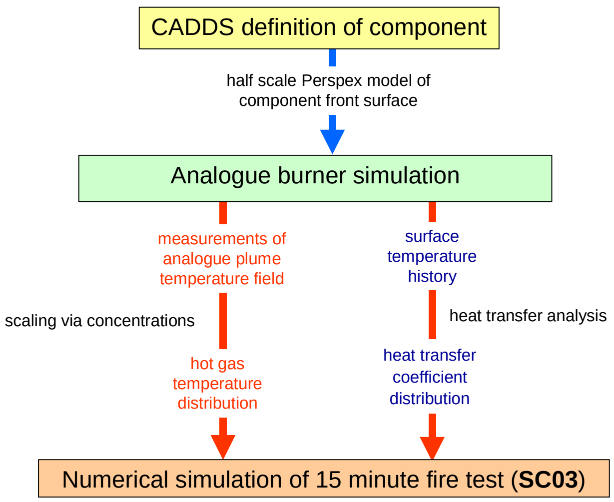

Figure 11. Detail of the methodology for determining boundary conditions from the analogue burner tests.

3.5 Mapping the adiabatic wall temperature distribution

The external flow field that results from both the impingement of the hot burner flow onto the model and the mixing of the flow with the surrounding ambient air is highly three dimensional and turbulent.

The heat transfer analysis of the fire test requires knowledge of both the local heat transfer coefficient and local adiabatic wall temperature. As with the distribution of *h*, the distribution of T_{aw} must be determined experimentally as it will be specific to each model tested. If a uniform temperature field is assumed directly downstream of the burner (post-combustion) then the variation in temperature of the subsequent impinging flow field is due only the fluid dynamic mixing of the hot burner plume with the surrounding cold ambient air. As stated, radiation loss from the flame is minimal, and this is certainly true for the low-temperature analogue burner. Thus the local gas temperature is simply a function of the relative concentrations of burner exit flow and ambient air.

In the original analogue burner tests, the distribution of local gas temperature was determined by direct measurement [3]. Surveys of T_{aw} were made using a rake of fine gas thermocouples (Figure 12).

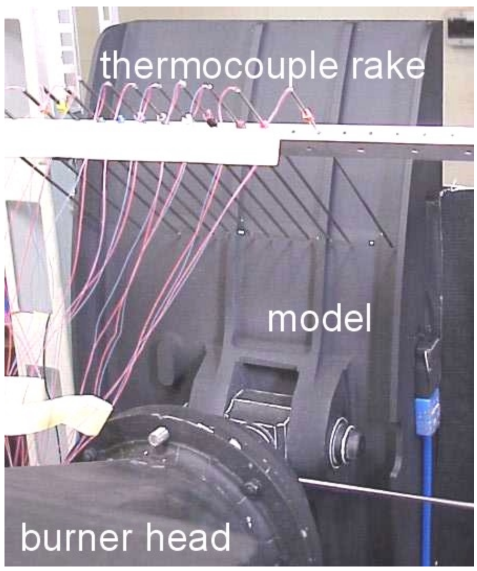

Figure 12. Surveys of T_{aw} across model surface using a thermocouple rake.

An example of the distribution of T_{aw}, interpolated from rake measurements across the intercase model, is shown in Figure 13. As expected, the peak gas temperatures are at the impingement point of the burner plume onto the model. The gas temperature decreases away from this point as turbulent mixing with the surrounding air dilutes the plume.

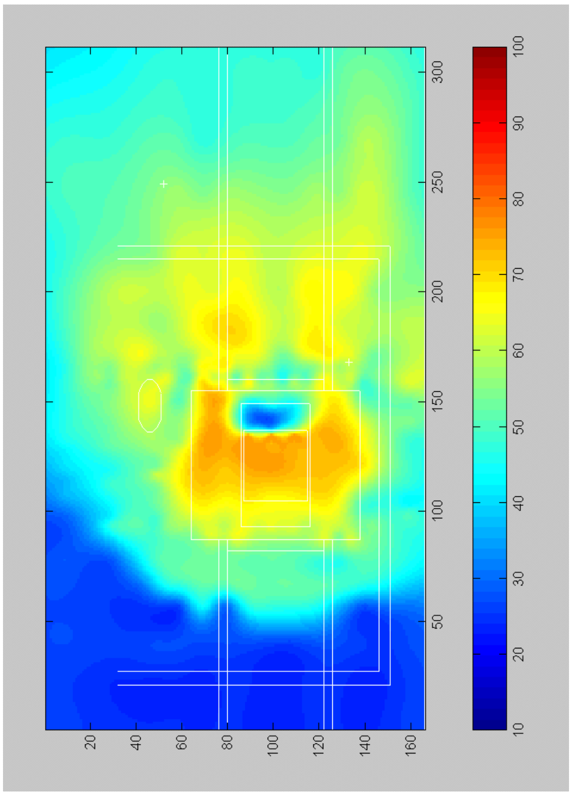

Figure 13. Measured T_{aw} distribution across half scale intercase model (°C).

To scale gas temperatures to the hot burner case, we must account for the temperature and specific heat ratios, which are not reproduced in the low-temperature analogue burner tests [3]. The temperature of the mixed region (T_m) is governed by the enthalpy of the mixture (H_m), as calculated from the mass fractions (M) in the plume and the surroundings by

$$H_m = H_p \,.\, M_p \;+\; H_o \,.\, M_o \qquad (6)$$

thus

$$T_m = \frac{C_{p,f,T_f}.T_f.M_f + C_{p,o,T_o}.T_o.M_o}{C_{p,f,T_m}.M_f + C_{p,o,T_m}.M_o} \qquad (7)$$

This is in fact the local adiabatic wall temperature and here the values of specific heat must be evaluated at the local mixture temperature. As the variation of C_p with temperature is small, the iteration required to arrive at a solution is minimal. The unknown mass fractions can be determined from the low-temperature experiment given that they must sum to unity. Equation (7) can thus be rearranged to allow the direct calculation of the two mass fractions.

$$M_o = \frac{C_{p,f,T_f}.T_f + C_{p,f,T_m}.T_m}{T_m\left(C_{p,o,T_m} - C_{p,f,T_m}\right) - C_{p,o,T_o}.T_o + C_{p,f,T_f}} \qquad (8)$$

The specific heat of the mixture can then be determined from

$$C_{p,m} = C_{p,p} \,.\, M_p \;+\; C_{p,o} \,.\, M_o \qquad (9)$$

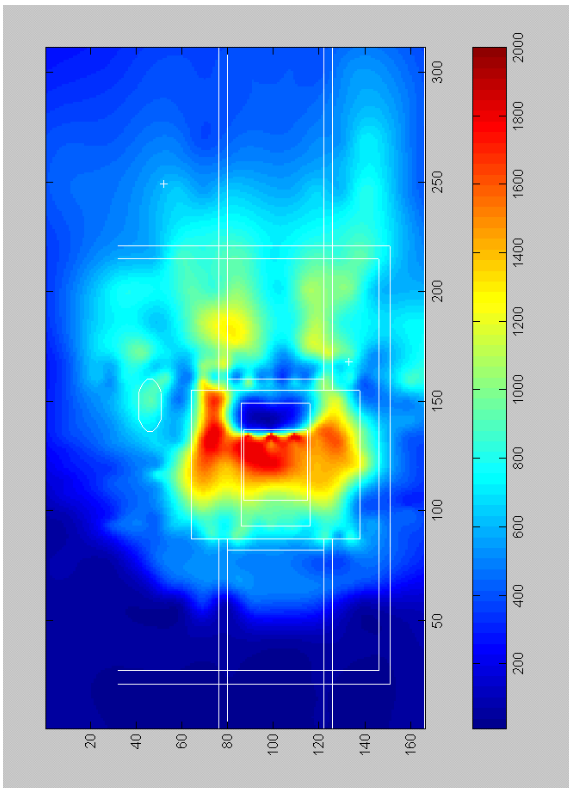

Figure 14. Scaled T_{aw} distribution across component in fire test (°C).

When the h levels are scaled to the flame condition, the local flame temperatures to be applied as boundary conditions can be determined in the same manner.

$$T_{aw} = \frac{C_{p,f}.T_f.M_f + C_{p,o}.T_o.M_o}{C_{p,f}.M_f + C_{p,o}.M_o} \qquad (10)$$

Once again the local specific heats of the two components must be determined iteratively with the local gas temperature. The distribution of T_{aw} for the standard fire test may thus be determined (Figure 14).

3.6 Validation of the analogue technique

Shadowgraphs and gas temperature surveys have been used to confirm the low-temperature simulation of the standard burner flow field [3]. Calibrations of the analogue burner have been performed using standard test pieces to confirm that the heat flux scales correctly to the fire test conditions [3][15]. Simulations of actual fire tests on complex components indicate good agreement between measured (Figure 15) and calculated metal temperature histories (Figure 16) [3][15].

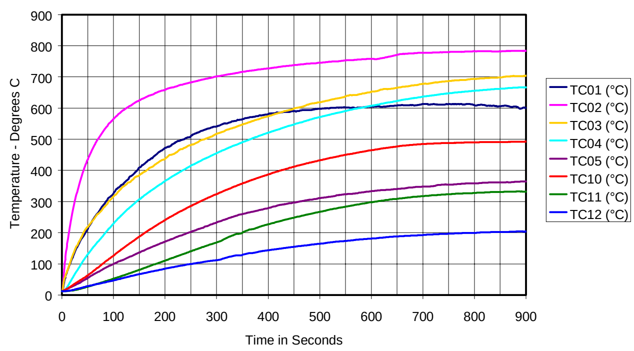

Figure 15. Metal temperature histories from actual fire test of rear mount ring [4].

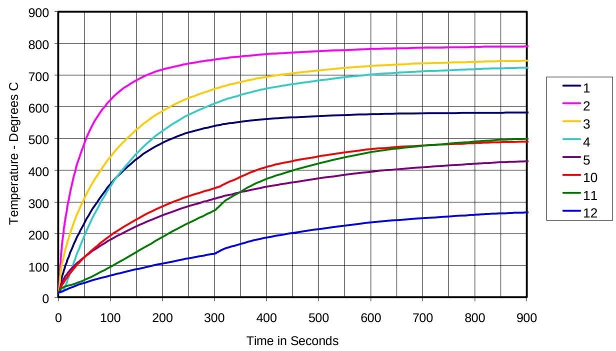

Figure 16. Metal temperature histories from numerical simulation of rear mount ring fire test [15].

3.7 Advantages of the technique

The low temperature analogue technique offers a number of significant advantages over the standard hot burner technique (Table 1). The ability to test at low temperature enables the use of liquid crystal coated plastic models, which are cheap and easy to manufacture. The use of liquid crystal provides metal temperature data at significantly higher resolution than that available from the standard fire test. The removal of the requirement for a flight worthy component and the ease of testing enable the low-temperature analogue technique to be easily incorporated into the overall design process. Aircraft engine components can thus be tested for fire integrity before the design is finalised. This is a major advantage as the need to meet a strict mass budget can often necessitate the removal of mass from these critical components, which can often have a negative impact on fire integrity. Thus the ability to fire test during the design process can lead to a more efficient design.

Table 1. Comparison of new low-temperature analogue technique with old fire test methodology.

Attributes	Standard fire-test	Low-temperature Analogue Technique
Gas temperature	1800 °C	90 °C
Scale	full	half
Test article	flight-worthy component	plastic model
Fast	✗	✓
Cheap	✗	✓
High resolution	✗	✓
Easily incorporated into design path	✗	✓

4 Development of Compact Analogue Burner

The most time consuming step in the pilot low-temperature analogue burner technique is the requirement for extensive gas temperature surveys across the model. This requirement necessitates up to a dozen additional tests to map T_{aw}. Development of the transient heat transfer coefficient mapping technique using multiple liquid crystal coatings will enable the simultaneous mapping of both h and T_{aw} in a single test (Figure 17) [16].

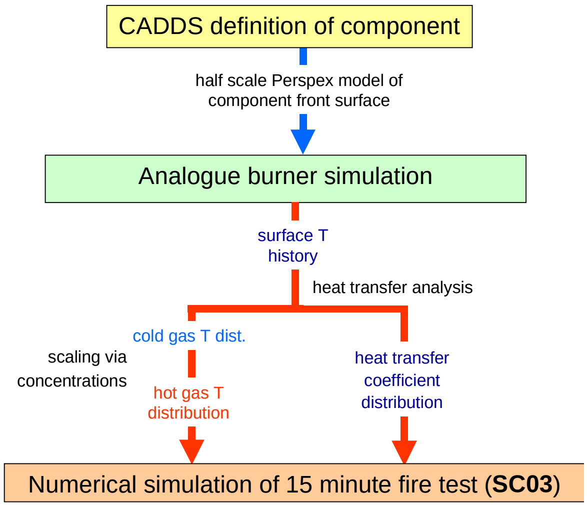

Figure 17. Development of methodology.

An additional modification under development is to replace the thick polycarbonate burner faceplate (5 mm), with a thin Mylar sheet (0.1 mm) [12]. The use of a thin sheet significantly reduces the thermal mass of the faceplate negating the need for the warm up phase and thus the shutter. The exit temperature of the burner will directly follow the mesh heater temperature. This will further enable the use of temperature stepping, to increase the accuracy of the technique. Here T_{aw} is varied in a series of steps to induce multiple crystal transitions to increase the dataset from which h and T_{aw} are deduced (Figure 18) [16].

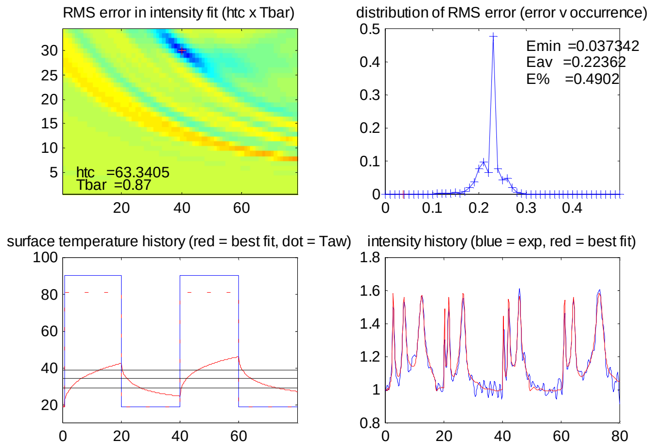

Figure 18. Combination of multiple crystal coatings and multiple temperature steps to reduce the uncertainty in the determination of h and T_{aw}.

5 Conclusions

The low-temperature analogue burner technique offers a cheap, fast, high-resolution alternative to standard fire testing. It is easily incorporated into the engine design process, enabling greater design efficiency. Further developments to the low-temperature analogue technique enhance the ease of use and the accuracy of the technique.

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