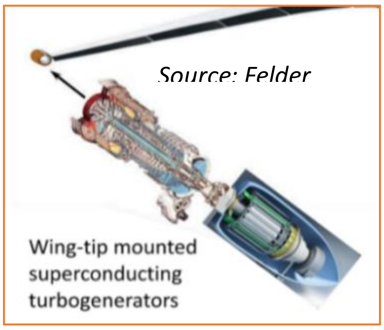
WP5: *Thermal Management.* Lead: Morvan at Nottingham.



Overview. For the foreseeable future, gas turbine engines will continue to play a crucial role. Initially they will retain their generic current form as primary propulsors. In the medium-term more electric aircraft, they will propel and generate power in hybrid propulsion systems. Longer term, their role will be as on-board electric power generation systems in full electric propulsion systems. Collocation of generators with the gas turbine region is an inevitable requirement. Coupled with the immediate drive towards lighter, more compact high speed engine cores and adoption of power gearboxes for some systems, this will create new challenges in coolant delivery and thermal management.

Background and motivation. Gas turbine engines and electrical machines have in common that the achievable power density and specific power are limited ultimately by the ability to remove heat. The reliable prediction of heat generation, transport and cooling in these machines is also key to modelling the operating thermal environment and thermal-mechanical response of the machine structures. Cooling arrangements in gas turbines presently rely primarily on supplying oil to relevant components. Jets or mist sprays may be used to form a film of oil on the target surface. This also requires the effective extraction of coolant; current approaches require significant mass flow rates of oil. In the case of electrical generators and motors, air cooling has become insufficient; liquid cooling is required to manage heat and to allow their integration in electro-mechanical systems. Longer term cryogenic cooling is envisaged as the key to unlocking the benefits of superconductivity for all electric propulsion.

Main elements of work. Work under this pillar sub-divides into 4 main tasks which address aspects of heat generation, droplet heat transfer, air-coolant interactions and light-weight material thermal performance. Toward the end of the programme, and in collaboration with Rolls-Royce, we will explore 2-phase flow modelling work with heat transfer and mass transfer (5th task) in support of cryogenic cooling as the company electrification strategy is formed. This is not described here.

Task 1: Coolant droplet dynamics and heat transfer. Oil supplied for lubrication and cooling of surfaces is often atomised and interacts with the surrounding air flow before deposition on surfaces [6]. This process significantly affects the heat transfer between the oil film and stator wall as well as oil chemistry and degradation. It is therefore essential to understand the lubricant droplet vaporization and breakup dynamics in convective heating environment in order to adequately model the subsequent surface cooling. The proposed work will build on our own work led by Rudrasetty and Mitchell and recent approaches [1],[2] and [8] by extending the range of fluid properties and considerations to aero-engine representative conditions. Oil droplets will be suspended; (a) in an acoustic levitator (See [7]) and heated by a continuous-wave laser; (b) from a cross-wire (1-2 mm size droplets) and heated by a vertical hot air stream as in [1],[2]. Droplet diameter, vertical stream velocity, air stream temperature will be measured. Oil evaporation rates and the droplet temperature distribution will be determined at different hot air stream velocities and temperatures. Proper orthogonal decomposition of HS images will be employed to determine the dominant droplet instability modes. Finally, the instability mechanism (e.g. ligament breakup, rim breakup, complete rupture) responsible for parent droplet breakup will be identified. Empirical correlations will be developed. In addition, droplets will be seeded with tracer particles and visualized to understand the flow pattern inside the droplets.

Task 2: Characterisation of air-coolant interface dynamics. Turbulence dissipation at the interface of shear driven lubricant/coolant films plays an important role in momentum and heat transfer between the gas and the film as well as the ultimate lubricant distribution and cooling of surfaces in gas turbines. In reality the interface is a deformable surface with a complex interaction between surface-tension forces, viscous forces and fluid inertia and not a rigid surface (with a simpler inertia-viscous balance) as commonly assumed in CFD after [3], including recent work by Morvan and Bristot at Nottingham [13]. The semi-empirical nature of the associated turbulence damping factor introduces additional uncertainty into the CFD model, a key obstacle to right-first time prediction. Experimental gas-liquid velocity measurements and scale resolving CFD models will be used to derive an improved understanding of the flow turbulence at the liquid-gas interface and the interaction of surface tension, viscous and inertia forces in shear driven laminar liquid films. A wavy film flow will be setup in a rectangular shearing and vertical annular flow rigs at Nottingham. Several different liquids be used for the study, since surface tension, viscosity and density can be theorised as important for these transitions. Engine representative Re, We and Fr will be targeted for evaluation. A combination of PIV and BB-LIF are proposed to investigate the transitions from 2-D to

3D waves and the transition from 3D to disturbance waves after the work of [10] and previous work by [11] and [12] at Nottingham. Direct measurements of instantaneous interface shear stress and both liquid and gas phase velocities will be obtained [10]. A fluorescent technique will be used to get instantaneous depth of the film over a large area (0.4 x 0.161 m) in the duct for comparison [11]. The experimental cases will be reproduced using scale resolving CFD models such as LES or Hybrid RANS/LES and the models validated against experimental observations. Based on the experimental and numerical results, improvements would be proposed for interface turbulence damping in non-scale-resolving RANS simulations.

Task 3: Modelling heat generation at very highly loaded gear contacts. To design more efficient gearboxes and minimise power losses, there is need to improve upon existing knowledge on oil behaviour and mechanisms of heat generation under highly loaded contacts which are present between the gear teeth. After a reduction of windage losses in the PGB, most of the heat generation is expected to come from shearing the oil film between the teeth. Ford et al [5] have previously demonstrated the dramatic difference in the frictional behaviour of different oils in the Hertz contact zone. In [4], Foord et al also looked at a range of lubricating oils and showed the significant effect of oil chemistry on the film generating capability. Oils of similar base viscosity but different chemistry can form oil films of very different thickness and shear strength in the concentrated contacts between gear teeth or in rolling contact bearings and this behaviour needs to be accurately characterised. The heat generated by this is fundamental to gear operation and needs to be fully analysed and understood in order to minimise its impact on the viability of high power aerospace reduction gearboxes. Computational Fluid Dynamics (CFD) and Elasto-HydroDynamics (EHD) modelling will be used. This will allow a greater understanding of what happens to the oil within these conditions, the factors influencing heat generation and how best to deliver optimum cooling, for instance using mist lubrication, if possible (to reduce oil flows). A parallel experimental campaign will also be carried out and results used to validate the CFD/EHD studies.

Task 4: Exploring ultra-light weight high temperature materials. The thermal efficiency of the engine is dominated by the capability of the hot section sub-systems (combustors and core turbines) in terms of cooling flow consumption, durability and maximum achievable combustor exit temperature. The desire for Rolls-Royce to increase propulsive efficiency, with reduced weight and cost, demands development of ultra-light weight high temperature materials, such as ceramic matrix composites (CMC) and 3D additive manufactured superalloys to replace conventional metallic components. The intention of this sub-task is to explore outstanding issues for successful implementation of these revolutionary high temperature materials into the aero-engine combustion subsystem, with an emphasis toward in-depth understanding of thermal capability and endurance behaviour of these materials under such harsh operating conditions and the development of predictive tools which utilise the material performance envelope. To carry out the proposed research, the existing testing facility at the University of Nottingham will be upgraded for ultra-high temperature application (i.e. for temperatures up to 1200 °C). This upgraded facility will then be used to acquire the high temperature material data under tensile, creep, fatigue and creep-fatigue interaction conditions which mimic the representative working environment of aero-engine combustors.

Overlaps with other parts of the programme. Task 3 will interact directly with the activities in WP1 at Oxford and task 1 will also insert itself in associated activities for couplings and gearboxes. Some of the outputs will also support the fluid-structure coupling activities for large assemblies in WP4. Task 5, on cryogenics, will support long term more electric activities, e.g. in WP6.

Interactions with other Universities. Interactions will primarily be with Oxford and with Rolls-Royce, in particular in relation to future core and power gearbox. We will support all relevant thermal-fluids activities too including the aero-thermal-structural modelling work at Imperial.

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