



# Investigation of the heat transfer coefficient in a transpiration film cooling with chemical reactions



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## ABSTRACT

In modern high performance engines (gas turbines, rocket combustors) the probability of chemical reactions inside a cooling film increases. In the past, the enhanced heat flux in a reactive cooling film is estimated usually using the difference between the hottest temperature inside the boundary layer and the wall temperature as driving temperature difference, assuming the heat transfer coefficient to be the same as in an inert configuration. However, experiments have shown that the heat transfer coefficient of a reactive cooling film differs from an inert one. The objective of this work is to investigate the heat transfer coefficient in a reactive boundary layer in more detail. The surface heat flux of a reactive laminar boundary layer on a transpiration cooled flat plate is analytically derived using boundary layer theory. The results of the simplified boundary layer theory are compared to CFD data for different reactive mixtures. In a reactive cooling film emanating with a mixture fraction  $Z = 1$  from a porous surface assuming Burke-Schumann chemistry, the heat transfer coefficient is mainly enhanced by a factor of  $1/(1 - Z_{st})$ , where  $Z_{st}$  is the mixture fraction at stoichiometric mixture. This factor represents the location of the maximum temperature within the boundary layer.

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## 1. Introduction

The design of modern gas turbines aims at high efficiency and short, lightweight combustors. Due to reduced mixing time, peak combustor exit temperatures rise and residual unburned fuel may be present. Since the inlet gas temperatures to the turbine stage exceed the melting point of the turbine blade material, film cooling is widely used to protect the turbine blades from the hot combustion products. Besides its application in gas turbines, present research in liquid rocket engines focuses on additional film cooling to cope with the increasing demand for thrust and efficiency.

Turbulent fluctuations of the main flow and diffusion processes can create a reactive mixture inside the cooling film. In combustors of gas turbines fuel-rich streaks may exit the combustion chamber and interact with the air cooling the turbine blades. This can lead to a heat release inside the cooling film and a drastic reduction in the cooling effectiveness [1]. A similar effect can arise when radicals or oxidizer pockets are transported into the fuel cooling film in a rocket combustion chamber.

The wall heat flux of a cooling film with chemical reactions is defined as a convective heat transfer coefficient and a driving tem-

perature difference  $\dot{q} = \alpha_{react} \Delta T$ . The driving temperature difference can be taken as the difference between maximum (flame) temperature in the boundary layer and the wall temperature [2,3]. The heat transfer coefficient  $\alpha$  is often assumed to be the same as in the inert case [2,3], which is equivalent to assuming that this maximum temperature occurs at the outer edge of the boundary layer. However, experimental data in gas turbine engines shows, that the heat transfer coefficient in a reactive boundary layer can increase from  $-5\%$  up to  $50\%$  compared to the inert value [2]. That means, that the surface heat flux is increased by a factor of up to 1.5 solely by the increase of the heat transfer coefficient.

The objective of this work is to derive an estimate of the unknown heat transfer coefficient  $\alpha_{react}$  of a reactive cooling film. In order to do this, a film cooling configuration in laminar flow is examined, where the cooling fluid is injected through a porous material (transpiration film cooling). The problem is thus simplified to a laminar boundary layer with chemical reactions. These flows have been studied in the scope of combustion over solid or liquid fuel [4,5] using boundary layer theory [11]. In these studies the injection into the boundary layer is directly coupled to the wall heat flux, since the fuel needs to be vaporized. In transpiration film cooling however, the heat flux and the injected mass are independent. Liu et al. [6] investigated a reactive flow over a porous surface with angled injection - both analytically and numerically. This group concentrated on parametric CFD studies to determine

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## Nomenclature

$C$	Chapman Rubesin parameter [-]
$c_p$	specific heat capacity at constant pressure [ $\text{J kg}^{-1} \text{K}^{-1}$ ]
$D$	mass diffusivity [ $\text{m}^2 \text{s}^{-1}$ ]
$f$	dimensionless stream function [-]
$H, L$	height, length [m]
$h$	enthalpy [ $\text{J kg}^{-1}$ ]
$K$	factor [-]
$p$	pressure [Pa]
$\dot{q}$	heat flux [ $\text{J m}^{-2} \text{s}^{-1}$ ]
$R$	specific gas constant [ $\text{J kg}^{-1} \text{K}^{-1}$ ]
$T$	temperature [K]
$u, v$	velocity [ $\text{m s}^{-1}$ ]
$W$	molar mass [ $\text{kg mol}^{-1}$ ]
$x, y$	coordinate [m]
$Y$	mass fraction [-]
$Z$	mixture fraction [-]
$\alpha$	heat transfer coefficient [ $\text{W m}^{-2} \text{K}^{-1}$ ]
$\delta$	boundary layer thickness [m]
$\lambda$	thermal conductivity [ $\text{W m}^{-1} \text{K}^{-1}$ ]
$\mu$	dynamic viscosity [ $\text{kg s}^{-1} \text{m}^{-1}$ ]
$\nu$	stoichiometric coefficient [-]
$\Psi$	stream function [ $\text{kg m}^{-1} \text{s}^{-1}$ ]

$\rho$	density [ $\text{kg m}^{-3}$ ]
$\xi, \zeta$	transformation coordinate

### Dimensionless quantities

$Le$	Lewis number $\frac{Sc}{Pr}$
$Nu$	Nusselt number $\frac{yX}{\lambda}$
$Pr$	Prandtl number $\frac{\mu c_p}{\lambda}$
$Re$	Reynolds number $\frac{\rho u x}{\mu}$
$Sc$	Schmidt number $\frac{\mu}{\rho D}$

### Indices

$ad, fl$	adiabatic flame
$i$	iteration
$inert$	without chemical reactions
$F, O$	fuel, oxidizer
$react$	with chemical reactions
$ref$	reference value
$st$	value at stoichiometric conditions
$W$	value at the wall
$\infty$	free stream value
'	differentiation with respect to $\zeta$
★	dimensionless values

controlling parameters on heat flux and surface temperature. In contrast to the work of Liu [6], the current work aims at the analytical derivation of a general description of  $\alpha_{react}$ .

In the first section of this paper the flow over a laminar transpiration film cooling configuration is investigated using boundary layer theory [7]. Varying fluid properties due to changes in temperature and composition are taken into account. Chemical reactions are simplified by a Burke Schumann approach. The results of the simplified boundary layer equations are then compared to numerical simulations with different reactive mixtures in the boundary layer. Special attention is paid to the parameters increasing the heat transfer coefficient  $\alpha_{react}$  in a boundary layer with chemical reactions.

## 2. Theoretical background

In this section the surface heat flux is derived from the similarity solution of a reactive boundary layer over a porous flat plate. The combustion is simplified here by a one-step Burke Schumann solution.

Fig. 1 depicts the investigated setup schematically. The fluid with the composition  $Z_\infty$  and the temperature  $T_\infty$  flows with the uniform velocity  $u_\infty$  over a porous flat plate. The coolant with the composition  $Z_w$  is injected through the porous material with

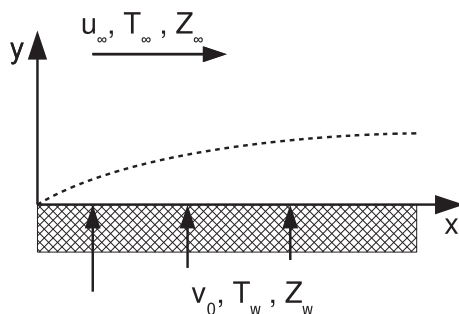


Fig. 1. Laminar flow over a porous flat plate, schematic.

the normal velocity  $v_w(x)$ . The wall and the coolant fluid are assumed to be in thermal equilibrium. So the coolant temperature  $T_c$  is equal to the wall temperature  $T_w$ . The porous plate is assumed to be ideally smooth, meaning the pores of the material and the fluid jets from the pores do not present obstacles for the flow. A laminar boundary layer develops on the plate. The reference point of the coordinate system is the upstream edge of the flat plate. The  $x$ -coordinate represents the downstream direction, the stream wise velocity component is  $u$ . The  $y$ -coordinate describes the distance to the plate surface, and  $v$  is the velocity component perpendicular to the plate. This setup represents an ideal transpiration film cooling situation.

The conservation equations of mass, momentum, energy and mixture fraction can be simplified using boundary layer theory [7]

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \quad (1)$$

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = -\frac{dp}{dx} + \frac{\partial}{\partial y} \left( \mu \frac{\partial u}{\partial y} \right) \quad (2)$$

$$\rho u \frac{\partial h}{\partial x} + \rho v \frac{\partial h}{\partial y} = \frac{\partial}{\partial y} \left( \frac{\mu}{Pr} \frac{\partial h}{\partial y} \right) \quad (3)$$

$$\rho u \frac{\partial Z}{\partial x} + \rho v \frac{\partial Z}{\partial y} = \frac{\partial}{\partial y} \left( \frac{\mu}{Sc} \frac{\partial Z}{\partial y} \right), \quad (4)$$

with the boundary conditions

$$\begin{aligned} y = 0: & \quad u = 0 \quad v = v_0(x) \quad h = h(T_w, Z_w) \quad Z = Z_w \\ y \rightarrow \infty: & \quad u = u_\infty \quad v = 0 \quad h = h(T_\infty, Z_\infty) \quad Z = Z_\infty \end{aligned} \quad (5)$$

The pressure gradient in Eq. (2) is induced by a density gradient in the boundary layer and is negligible in the free stream ( $y \rightarrow \infty$   $dp/dx = 0$ ). The energy conservation equation is written in terms of the enthalpy including the heats of formation. The Eckert number is assumed to be very small and viscous heating therefore negligible. Radiation heat losses are neglected, too. The mixture is described by a conserved scalar. In this configuration a cooling fluid with a fixed composition  $Z_w$  is injected into the boundary layer without interacting with the porous material. In case of an e.g. ablation cooling the boundary condition needs to

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