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Improvement of wall condensation modeling with suction wall functions for containment application

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HIGHLIGHTS

- Assessment of wall functions for single phase condensation models for large scale application.
- Identification of modeling errors related to standard log-law due to buoyancy and wall normal mass transfer (suction).
- Modeling of wall normal mass transfer by literature formulation (Sucec, 1999) and in-house approach (FIBULA).
- Validation against isothermal Favre experimental data.
- Comparison against reference fine grid solution for condensing conditions.

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ABSTRACT

To simulate wall condensation on containment scale with CFD methods at reasonable computational cost, a single phase approach has to be applied and wall functions have to be used. However, standard wall functions were derived for flows without heat and mass transfer and their fundamental simplifications are not appropriate to deal with condensation. This paper discusses the limitations of standard wall functions and proposes two wall functions for the momentum equation dealing with mass transfer normal to the sheared wall (suction). The first proposed suction wall function is an algebraic modification based on the standard wall function concept. The second proposed wall function is an in-house developed suction wall function with the potential to cover also heat and mass transfer effects by storing the complex solutions of the RANS-Equations in a lookup table. The wall function approaches are compared to experimental results for boundary layer flows with suction and to the reference results obtained using a refined grid in order to resolve the condensing boundary layer.

1. Introduction

During a postulated loss of coolant accident with core degradation, steam and hydrogen are released into the containment, where the hydrogen can locally accumulate and form ignitable gas mixtures. Steam condensation on the cold structures influences the local distribution of hydrogen in two ways. First, due to condensation, hydrogen might locally accumulate and overcome flammability limits with oxygen. Second, condensation introduces buoyancy forces near the wall, which drive the turbulent mixing in the main flow. Thus, wall condensation of steam is of particular importance to predict the risk of a containment failure during severe accidents.

To simulate condensing flows in large geometries, it is necessary to introduce two major simplifications in order to limit the computational cost. First, the condensate film is neglected, and condensation is modeled as a single phase phenomenon by means of a mass transfer approach (Kelm, 2010; Zschaeck et al., 2012). Second, wall functions are introduced in order to reduce the necessary grid resolution in the boundary layer. In current CFD codes, wall functions are based on the well-known 'log-law' or 'law of the wall', which describes the dependency between the non-dimensional wall distance y^+ and velocity u^+ by means of a theoretical derivation with empirical constants in a fully developed flow (Wilcox, 2006). During condensation at the walls, two main effects occur which lead to a deviation from the log-law wall function approach and introduce modelling errors. First, buoyancy effects occur in

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Symbols

Symbol	description (unit)
A	damping length in the damping function by van Driest (m)
A^+	non-dimensional suction rate according to Favre (−)
C	integration constant in the log-law (−)
g_x	gravitation in x-direction $\left(m/s^2\right)$
m	fluid mass (kg)
p	pressure (Pa or kg/ms^2)
t	time (s)
T	temperature (°C)
u	velocity in x-direction (parallel to the wall) $\left(m/s^2\right)$
u_τ	shear velocity $\left(m/s^2\right)$
v	velocity in y-direction (normal to the wall) $\left(m/s^2\right)$
x	local variable along the wall (m)
y	local variable orthogonal to the wall (m)
κ	von Karman constant ~0.4 (−)
μ	dynamic viscosity $\left(kg/ms^2\right)$
μ_t	turbulent viscosity $\left(kg/ms^2\right)$
ρ	mixture density $\left(kg/ms^2\right)$
τ	shear stress $\left(N/ms^2\right)$

Superscripts

+	variable in non-dimensional form

Subscripts

l	laminar
t	turbulent
suc	suction (positive direction towards the wall)
w	condition at the wall

condensing boundary layer due to density differences resulting from wall-normal temperature and species gradients. Second, the so-called 'suction effect', which describes the wall-normal mass transport, affects the wall-normal non-dimensional velocity profile, as demonstrated in the experiments by Favre et al. (1966) (see Fig. 1).

This paper discusses the modeling limitations of different wall function approaches when modeling suction effects while buoyancy effects are not covered. The discussion is based on a comparison to a fine-grid solution obtained by means of the k–ω Shear Stress Transport Model. Besides the standard wall function, two velocity wall functions, which consider suction effects, are addressed. The first suction wall function is an adaption of the power law approximation by Sucec (1999). The second is an in-house developed wall function, which is based on a numerical solution of the momentum equation over the full boundary layer and can be used to address additional effects such as buoyancy in the future, too.

2. Wall functions

In CFD simulations, when it is not possible to use a fine grid discretization in the boundary layer due to its high numerical cost, wall functions are applied to represent the near-wall processes on a coarse grid. Instead of solving all conservation laws in 3D at multiple cells on a fine grid, the flow close to the wall is assumed to be a wall parallel flow. Consequently, simplified Reynolds-averaged Navier–Stokes (RANS) equations can be applied and the different variables (velocity, temperature, species) can be expressed as functions of the wall distance. These functions provide the, on a coarse grids missing, flow information in the boundary layer as boundary conditions for the first node to the CFD simulation and are called wall functions.

2.1. Standard wall function

Relevant for the velocity profile in the boundary layer is the Reynolds-averaged momentum Eq. (1) in the flow direction x parallel to the wall.

$$\frac{\partial}{\partial t}\left(\rho(y)u(y)\right)+\frac{\partial}{\partial y}\left(-\rho(y)v_{\mathrm{suc}}u(y)\right)-\frac{\partial}{\partial y}\left(\mu(y)\frac{\partial}{\partial y}u(y)+\mu_t(y)\frac{\partial}{\partial y}u(y)\right)=-\frac{d}{dx}p(x)+\rho(y)g_x \tag{1}$$

To solve Eq. (1), the following simplifications are introduced.

1. A time independent flow	$\frac{\partial}{\partial t}(\rho u)=0$
2. A fully developed flow	$u(x,y)=u(y)$
(no streamwise change of flow variables)	$\mu_t(x,y)=\mu_t(y)$
3. No velocity normal to the wall (suction)	$v_{\mathrm{suc}}=0$
4. Constant density	$\rho(y)=\rho$
5. Constant material properties	$\mu(y)=\mu$
6. No pressure gradients	$\frac{d}{dx}p=0$
7. No gravity forces	$g_x=0$

With these simplifications, the momentum equation is simplified to:

$$\frac{\partial}{\partial y}\left(u\frac{\partial}{\partial y}u(y)+u_t(y)\frac{\partial}{\partial y}u(y)\right)=0 \tag{2}$$

Eq. (2) can be solved for two regions (Laurien, 2010). First, a thin laminar layer close to the wall, where the turbulence can be neglected ($u_t(y)=0$), and second, for the fully turbulent part, where the molecular viscous forces can be neglected ($\mu=0$).

To simplify these equations, non-dimensional variables for the velocity μ (3) and the normal wall distance y (5) are used (index '+').

$$u^+=\frac{u}{u_\tau} \tag{3}$$

In doing so, the characteristic velocity is the shear velocity, calculated with the wall shear stress τ_W (4).

$$u_\tau=\sqrt{\frac{|\tau_W|}{\rho_W}} \tag{4}$$

In a similar way, the non-dimensional wall-normal distance y^+ (5) is formulated.

$$y^+=y\frac{\sqrt{|\tau_W|\rho_W}}{\mu} \tag{5}$$

While neglecting turbulence, Eq. (2) can be solved with two boundary conditions (6) and (7) starting from the wall.

$$\mu\frac{\partial}{\partial y}u(0)=\tau_W \tag{6}$$

$$u(0)=0 \tag{7}$$

Therefore, the laminar solution in non-dimensional form can be evaluated to (8):

$$u_l^+=y^+ \tag{8}$$

For the turbulent region, where the molecular viscosity is neglected, the solution is more complicated. Because there are no direct boundary conditions that can be used, a local equilibrium between the shear in the turbulent region and the shear at the wall