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"Stagnation flow heat transfer of confined, impinging hot water jets under supercritical pressures"

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ABSTRACT

Hydrothermal spallation drilling is a possible alternative drilling technology based on the characteristics of certain rock types to disintegrate continuously into small fragments when exposed to high thermal loads. Impinging supercritical water jets or hydrothermal flames are favored to provide the required heat for thermal fragmentation.

Hence, stagnation flow heat transfer under supercritical pressures of water was investigated by means of two calorimetric sensor devices covering a wide range of heat fluxes and surface temperatures. A numerical model based on ANSYS FLUENT was established to predict the heat transfer in conjunction with the Shear-Stress Transport k–ω turbulence model and the REFPROP database to calculate the thermo-physical properties. Finally, area-averaged heat transfer coefficients in the stagnation region of impinging hot water jets were determined by numerical simulations and validated against experimental measurements. Generally, the experimental trends were predicted correctly by the numerical model although the absolute heat transfer was overestimated.

1. Introduction

1.1. Hydrothermal spallation drilling

Hydrothermal Spallation Drilling (HSD) [1–3] is considered as a possible alternative technology for drilling deep wells in hard rock formations. This approach is based on the characteristics of certain rock types to disintegrate continuously into small disk-like fragments (spalls) when exposed to the high thermal loads [4–6] of an impinging hot jet (see Fig. 1). The heat transfer between impinging hot jet and rock was identified as crucial parameter in the spallation drilling process and high heat fluxes ($\approx$1 MW/m^2) are required for successful penetration [7]. Enhanced drilling velocities and less wear of the drilling head in hard rocks are expected that finally contribute to the reduction of drilling costs [8]. Moreover, also thermally-assisted drilling [9] by combining conventional rotary drilling (state of the art) and HSD is evaluated as promising [10]. When rock is heated up rapidly to high surface temperatures by an impinging flame jet, stresses and fractures are generated in the upper layers facing the heat. All these events weaken the rock and afterwards, less torque and weight on bit is required to remove the rock (see [11], p. 140). This finally leads to reduced wear and longer drill bit life time.

For drilling deep (e.g. geothermal) wells of several kilometers depth, a water-based drilling fluid is essentially required for several important tasks in the drilling process, e.g. removal of rock cuttings (spalls, see Fig. 1) [13]. In water filled boreholes at certain depth, the pressure exceeds the critical pressure of water (p_c = 220.64 bar) and therefore, supercritical water (SCW) jets [12] or hydrothermal flames [14] are of particular interest to provide the required heat for HSD.

In the transient heating process during spall formation, the rock surface temperature starts at the comparably low initial rock temperature of the newly exposed surface. Due to the impinging hot jet, the surface temperature rises quickly with time till the next spall is ejected at a high rock surface temperature. Therefore, the characteristics of the heat transfer coefficient (h) with respect to surface temperature (T_s) and heat flux ($\dot{q}$) are of great importance for HSD. Depending on the initial rock temperature, the fluid conditions in the boundary layer adjacent to the rock cross the critical (p_c = 220.64 bar, T_c = 374 °C) and the pseudo-critical point (PCP) of water (p_{pc}, T_{pc}), respectively. In the supercritical state, the

Abbreviations: CFD, computational fluid dynamics; CuCr1Zr, copper alloy; HSD, hydrothermal spallation drilling; HW, hot water; LES, large eddy simulation; PCP, pseudo-critical point; PCT, pseudo-critical temperature; PTFE, polytetrafluoroethylene; RANS, Reynolds-averaged Navier–Stokes equations; SCW, supercritical water; SSTKW, shear-stress transport k–ω; UDF, user defined function.

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Symbols

A	[m^2] area
A_s	[m^2] (surface) area sensor
c_p	[J kg^{-1} K^{-1}] specific isobaric heat capacity
d	[m] diameter, characteristic length
d_{con}	[m] inner diameter cylindrical confinement
d_{ext}	[m] external nozzle diameter
d_s	[m] sensor diameter
d_0	[m] inner nozzle exit diameter
D	[m] separation distance between nozzle exit and plate
h	[W m^{-2} K^{-1}] heat transfer coefficient
k	[m^2 s^{-2}] turbulent kinetic energy
$\dot{m}_0$	[kg s^{-1}] hot water mass flow rate
Nu	[dimensionless] Nusselt number
p	[Pa] pressure
p_c	[Pa] critical pressure
p_{pc}	[Pa] pseudo-critical pressure
Pe_t	[dimensionless] turbulent Péclet number
Pr	[dimensionless] (molecular) Prandtl number
Pr_t	[dimensionless] turbulent Prandtl number
$\dot{q}$	[W m^{-2}] heat flux
$\dot{Q}$	[W] transferred heat from fluid to solid surface
r	[m] radial coordinate
Re	[dimensionless] Reynolds number
Re_0	[dimensionless] nozzle exit Reynolds number
T	[°C] temperature
T_c	[°C] critical temperature
T_f	[°C] reference fluid temperature
T_g	[°C] guard temperature
T_{pc}	[°C] pseudo-critical temperature
T_s	[°C] surface temperature (sensor or rock)
T_0	[°C] nozzle exit temperature
u	[m s^{-1}] velocity
v^2	[m^2 s^{-2}] velocity scale
x	[m] axial coordinate
y	[m] wall normal distance
y^+	[dimensionless] dimensionless wall distance
ε	[m^2 s^{-3}] turbulent dissipation rate
λ	[W m^{-1} K^{-1}] thermal conductivity
λ_t	[W m^{-1} K^{-1}] turbulent thermal conductivity
μ	[kg m^{-1} s^{-1}] dynamic viscosity
μ_t	[kg m^{-1} s^{-1}] turbulent (eddy) viscosity
ρ	[kg m^{-3}] density
ω	[s^{-1}] specific dissipation rate

thermo-physical properties (or rather the Prandtl number) vary significantly around the pseudo-critical temperature (PCT) [15] throughout the entire wall boundary layer (see Fig. 8). The dimensionless heat transfer (Nusselt number $Nu = hd/\lambda$) is generally correlated by the Reynolds number ($Re = u\rho d/\mu$) and the Prandtl number ($Pr = c_p\mu/\lambda$). Therefore, the thermo-physical fluid properties strongly affect convective heat transfer. A short overview linked to heat transfer phenomena under supercritical pressures is given in the next paragraphs.

1.2. In-tube heat transfer under supercritical pressures

Generally, the use of supercritical fluids in thermodynamic cycles of power plants and as an environmental friendly refrigerant is of growing interest. Therefore, several investigations are available in literature dealing with heat transfer at subcritical ($p > p_c$, $T < T_c$), transcritical ($p \approx p_c$, $T \approx T_c$) and supercritical ($p > p_c$, $T > T_c$) conditions. Heat transfer phenomena of water and carbon dioxide flowing through heated (heating conditions) or cooled (cooling conditions) tubes were frequently studied.

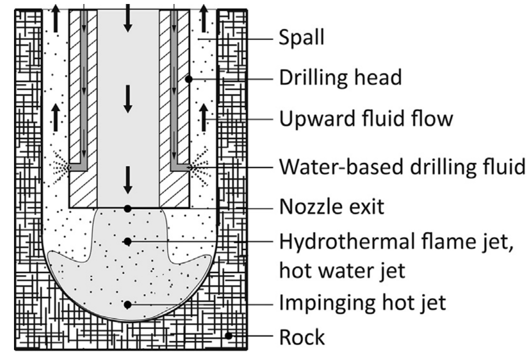

Fig. 1. Possible hydrothermal spallation drilling head in operation [12].

Most researchers applied an electrically heated coil along a tube to heat up the fluid flowing through (heating conditions). At high mass flow rates of water, the highest heat transfer coefficients are detectable for low heat fluxes when the bulk temperature is close to the pseudo-critical temperature (e.g. [16]). The water inside the entire wall boundary layer has a temperature close to T_{pc} and hence high c_p values are present there. The "integrative effect" [17] of these high c_p values (or rather Pr) present throughout the entire wall boundary layer leads to high heat transfer coefficients (enhanced heat transfer). On the other hand, when the heat flux is rising, the high c_p values in the wall boundary layer become more localized which leads to decreasing heat transfer coefficients ("deterioration or impairment of heat transfer") [18,19].

Significantly less literature is available for experimental configurations, where the heat transfer is vice versa, from the hot fluid to the cooled wall of a tube (cooling conditions). Different studies on in-tube heat transfer to supercritical carbon dioxide were undertaken (e.g. [20–22]). For constant property fluid flow, it is known that the heat transfer is identical for heating and cooling conditions. But due to the variations of the thermo-physical properties with respect to temperature and pressure (see Fig. 8), the heat transfer is strongly affected by the direction of the heat exchange. According to Dang and Hihara [21,22], the reverse distribution of the thermo-physical properties inside the wall boundary layer is the reason for the differences in heat transfer between heating and cooling conditions at supercritical pressures. Isobaric heat capacity (c_p) and thermal conductivity (λ) are the properties that mainly affect this heat transfer.

Generally, heat transfer is more intense under cooling conditions compared to heating. Under cooling conditions, the maximal h value around the PCT is higher with respect to the corresponding heating conditions. For heating, h decreases with increasing $\dot{q}$, whereas under cooling, h generally increases with increasing $\dot{q}$. Except close to the PCT, the h peak values are slightly decreasing for increasing $\dot{q}$. Generally, an increasing heat flux has an inhibiting effect on the heat transfer under heating conditions, whereas this effect is significantly less pronounced under cooling conditions.

Dang and Hihara [21] also investigated the in-tube heat transfer of supercritical carbon dioxide under cooling and heating conditions by means of numerical methods. All numerical results for the heat transfer coefficient were compared to experimental data sets. Four low Reynolds number k–ε turbulence models were applied in the investigations. Moreover, the effect of a variable turbulent Prandtl number (Pr_t) on the simulated heat transfer was studied by formulating Pr_t as a function of Pr. The fluid properties of CO_2 were calculated using the REFPROP database. All used turbulence