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Heat transfer by liquid jets impinging on a hot flat surface ☆

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HIGHLIGHTS

- We modeled single and double jet hitting a surface in 2D and 3D.
- We studied heat transfer properties and compared the results with published model.
- Influence of the water flow rate on heat transfer was investigated.
- A correlation for position of the maximum Nusselt number was presented.
- We investigated the jet–jet interaction.

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ABSTRACT

Runout Table (ROT) cooling is one of the most important factors for controlling quality of hot rolled steel. ROT cooling uses large quantities of water to cool the steel plate. Optimizing heat transfer in the ROT would reduce the amount of water used, which will lower the amount of energy needed for pumping, filtering, storage and use of water. Optimization will therefore result in a direct energy saving as well as increasing the product quality.

This study investigates heat transfer by turbulent water jets impinging on a hot flat steel plate at temperatures below the boiling point in order to understand convection heat transfer phenomena. This is an important stage that precedes the boiling and addresses the applicability of the heat transfer correlations available in the literature.

A single axisymmetric jet and a pair of interacting jets are simulated using Computational Fluid Dynamics (CFD). The Reynolds Averaged Navier Stokes (RANS) model under steady and transient conditions and the k–ε turbulence model are used in both 2D axisymmetric and 3D simulations. We investigate the influence of the water flow rate on the jet cooling characteristics and develop a correlation for the radial position of the maximum Nusselt number based on numerical results.

Two sets of boundary conditions – constant temperature and constant heat flux – are applied at the surface of the steel plate and evaluated. The single jet numerical results compare favourably with published data based on measurements and analytical models. The thermal performance of a two-jet system was found to be no better than a single jet because the jets were too far from each other to generate any additional thermal interaction.

1. Introduction

The iron and steel market in china is the largest in the world. Therefore, several important investigations concerning energy cost savings and CO_2 emissions reduction have been focusing on the Chinese iron and steel sector (Li and Zhu [1], Chen et al. [2]). An existing study based on 41 energy saving technologies shows that the major energy saving potentials in 2020 and 2030 will be mainly from Electric Arc Furnace (EAF) technology (Li and Zhu [1]). The authors consider Improved Process Control particularly in the hot rolling as an important energy saving technology.

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Nomenclature

d	nozzle diameter (0.03 m)	r_2	radius of region II (m)
$D(Z)$	jet diameter (m)	r_3	radius of region III (m)
D_{min}	minimum $D(Z)$ (m)	Re_d	$=\frac{\rho U_f d}{\mu}$, Reynolds number
g	gravitational constant (9.8 m/s)	$r_{Nu_{max}}$	r for maximum Nu_d (m)
h	$=\frac{q''}{T_s-T_\infty}$, heat transfer coefficient (W/m^2 K)	T	temperature (K)
$h(r)$	liquid film thickness (m)	T_f	fluid temperature at inlet (293 K)
k	turbulent kinetic energy (kg m^2/s^2)	T_s	surface temperature (K)
k_f	thermal conductivity of fluid (W/m K)	T_∞	free stream fluid temperature (K)
$\dot{m}$	flow rate (kg/s)	U_f	fluid velocity at inlet (m/s)
Nu_0	Nusselt number at stagnation point	z_0	distance between nozzle and strip (0.2 m)
Nu_d	$=hd/k_f$, Nusselt number based on d	Z	distance downward from the nozzle (m)
Pr	Prandtl number	ρ	density (kg/m^3)
q''	$=-k_f\frac{\partial T}{\partial y}\Big\|_{y=0}$, heat flux (W/m^2)	μ	dynamic viscosity (kg/ms)
r	radial position (m)	δ	momentum boundary layer thickness (m)
r_1	radius of region I (m)	δ_T	thermal boundary layer thickness (m)
		ε	turbulent dissipation rate (kg m^2/s^2)

A system dynamic model and an energy system model were used by Chen et al. [2] to predict the future energy consumption and CO_2 emissions in the Chinese iron and steel industry. The authors confirm a significant increase in usage of the EAF technology in this sector and predict an increase from around 10% in 2010 to 45% in 2050. They emphasize that the reductions in energy and CO_2 intensities will rely on the respective energy saving technologies. Advanced modeling, simulation and prediction capability of cooling during hot rolling, provides valuable data to improve the design and the process control and strengthens several of the energy saving technologies considered by Li and Zhu [1].

The Runout Table (ROT) cooling is one of the most important processes in hot rolling and has one of the highest water consumptions of any industrial process (WssTP [3]). Due to the scarcity of this resource, its potential as an energy source and its importance in the life cycle and the environment, excessive consumption and use is unethical and even dangerous (Dubreuil et al. [4]). The huge quantity of water that the ROT process requires necessitates a large energy expenditure for transport from the water source to the hot metal strip. Pumping, filtering, storing, collecting and removing water containing large quantities of heat represents a major energy loss which has been identified by experts from all involved areas. To overcome these negative industrial impacts engineers and scientists are making major efforts to understand the various processes and phenomena involved in the ROT (Latzel [5], Pugh et al. [6]).

This work examines liquid impinging jets because of their ability to create heat transfer coefficients that can exceed 100 kW/m^2 K, thus cooling high flux surfaces that other single phase flow methods cannot. Computational Fluid Dynamics (CFD) tools and methods are often used to analyze energy distribution and management in industrial processes such as hot rolling, furnaces and boilers, electrical components and electronic packages where mixing and thermal management are important considerations. A small amount of optimization can provide large energy savings in processes like these that require large amounts of energy. There is an urgent need for suitable cooling prediction models implemented in a CFD framework to analyze, control and optimize various industrial processes where high heat fluxes are generated. Mastering the cooling processes, CFD methods and tools can contribute to building efficient and sustainable energy systems with lower energy and water consumption.

Efficient cooling methods allow for lower coolant flow rates, smaller cooling system volume (e.g. piping and pumps) and provide vital control of the critical hot spots that can dramatically reduce the installation life time or even damage the product or the system. For instance, in the hot rolling case, several tons of water may be used every hour to cool the steel to obtain the desired temperature profile for the production process. Accurately predicting the cooling process would allow optimization of the coolant flow rate and the operating mode, resulting in a large reduction in water consumption, storage facilities, pumping and filtration. This would have a very positive environmental impact and reduce the energy consumption.

Many different techniques are used to cool steel plates at the ROT, such as impinging water at different angles with different types of nozzles, sprays and liquid curtains. Among them, liquid impinging jets perpendicular to the plate with a circular nozzle (often called liquid bars) are commonly used because of their simple design, robustness and high heat transfer rates. Impinging air or water cooling techniques are very useful for other applications like cooling of combustion engines and electronic microchips (Sharma et al. [7]). The cooling process of the steel strip at the ROT is a special case of jet impingement cooling of a flat plate.

Modeling and predicting cooling of the hot flat strip under ROT conditions is very complex and is often dealt with using experiments and empirical models. This case combines strip movement with boiling phenomena and consequently becomes very difficult to model. In this work, we separate out the movement and boiling phenomena and focus mainly on two key characteristic parameters, the liquid flow rate representing the single phase convective heat transfer and the jet–jet interaction, excluding surface movement and phase change.

Two types of impinging jets are frequently used for cooling: free surface liquid jets and submerged jets. In this study we focus on free surface liquid jets. Fig. 1a shows a typical configuration of an axisymmetric jet. The zone beneath the jet is called the stagnation zone. This is the most important zone, where most of the complex physics associated with very intense cooling occurs. The radial flow zone is further divided into different regions depending on the thicknesses of the film, the momentum boundary layer and the thermal boundary layer, see Fig. 1b. The thickness of the liquid film can vary significantly for laminar and turbulent flow. The velocity of the liquid decreases with increasing radial distance from the stagnation point, and an important phenomenon called the hydraulic jump occurs.

Impinging water jet cooling has attracted a great deal of attention from many researchers over the last few decades. The main

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