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Research Paper

Forced convective heat transfer on a horizontal circular cylinder due to multiple impinging circular jets

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HIGHLIGHTS

- Consideration of bank of impinging circular jets with high d/D ratio.
- Results based on more than 100 computational fluid dynamics cases.
- For largest jets, heat transfer decreases with movement away from cylinder axis.
- For smaller jet, heat transfer increases with movement away from cylinder.
- Correlation concisely quantifies heat transfer for parametric range considered.

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ABSTRACT

A computational study is undertaken to investigate convective heat transfer on a horizontal cylinder due to a bank of vertically oriented circular jets. The importance of this study stems from the real-world application of convective cooling of rotary cement kilns by the use of large axial fans. A computational model is developed which considers one spatially-periodic section of the domain, and solutions of the conservation equations combined with an appropriate two-equation turbulence model are obtained using the commercial software Fluent™. The computational model is validated by a comparison to previous studies of a single circular jet impinging on a cylinder. A parametric study is presented which considers the impact on average heat transfer due to: jet-to-cylinder spacing (y/d), axial jet spacing (z/d), jet-to-cylinder diameter ratio (d/D), jet offset from the axial centerline (x/d), and jet Reynolds number. Results of the parametric study show that for jet-to-cylinder ratios of $d/D \geqslant 0.23$, that movement away from the cylinder axis, increased axial spacing and lateral offset all lead to degradation of heat transfer from the cylinder. For $d/D = 0.15$, similar degradation occurs, but in part of the parametric space studied, increased distance from the cylinder and lateral offset leads to enhancements of the heat transfer. The complete set of results is presented as a correlation wherein the influence of all parameters studied are included as power-law corrections to the average Nusselt number.

1. Introduction

Convective cooling of large cylinders by banks of fans has many applications in the process industry. A pertinent example is in the cement industry where large (4–5 m in diameter and 50–100 m in length) rotary kilns are utilized for the production of cement clinker. A schematic showing the layout of a typical rotary cement kiln is given in Fig. 1. Tilted at an angle of 2–5° with respect to horizontal, and operating at a slow rotational speed of approximately 1–5 rpm, the raw feed (typically limestone, silica, aluminum and iron oxide, Mujumdar and Ranade [1]) travels through the cylindrical kiln due to gravity/tumbling. The kiln itself is comprised of a steel shell for strength and rigidity, lined on the inner surface with refractory brick to enhance the thermal resistance, and isolate the steel shell from the high temperature process taking place inside. Raw feed enters the kiln at one end, and fuel (petroleum coke), which is combusted in a burner located approximately 1 m into the kiln, enters at the opposite end. Near the burner, the temperature of the exhaust gases can reach upwards of 2200 K, and the reacting raw material can reach as high as 1900 K. The solids begin to melt in this region allowing for the required solid-liquid reactions to occur. As this liquid mixture re-solidifies, tiny balls referred to as clinker are formed, as well as a thin coating layer adjacent to the inner refractory wall of the kiln. This process is essential to the formation of clinker, and requires significant heat

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Nomenclature

d	jet diameter, m	y^+	non-dimensional wall distance
D	cylinder diameter, m	V_J	airspeed of fluid at jet exit, m/s
y	jet-to-cylinder distance, m	h_{ave}	average heat transfer coefficient, W/m^2 K
z	axial distance, m	Nu_{ave}	average Nusselt number
x	jet offset from cylinder axis, m	k_f	thermal conductivity of fluid, W/m K
Re_d	jet Reynolds number	ε	turbulent dissipation rate, m^2/s^2
Re_D	cylinder Reynolds number	ν	kinematic viscosity, m^2/s
k	turbulent kinetic energy, m^2/s^2		

removal through the kiln wall to occur. To facilitate heat transfer through the kiln wall, banks of large kiln shell cooling fans are often used in the burning region of the kiln.

Positioning of the cooling fans requires consideration of the process occurring in the kiln, and the path that the heat takes to reach the outer wall of the kiln. Fig. 2 shows that the particle bed inside the kiln is skewed to one side, due to the slow rotation of the kiln, and that the particle bed is in contact with the only 10–15% of the refractory material at a time. While this produces a local hot-spot on the inner refractory surface, this hot spot is in continuous motion due to the rotation of the kiln. A report by Mastorakos et al. [2] indicates that the internal surface temperature can vary by ±50 K from an average temperature value. In their report, internal heat transfer is described as a "regenerative" process, wherein the refractory material receives heat when exposed to the flame and internal freeboard gas inside of the kiln, and then supplies heat to the tumbling raw material bed inside of the kiln as it passes underneath. In the "burning" region, where the fans are typically located, a melt forms inside of the kiln, which solidifies over the refractory brick forming the thin coating layer mentioned previously. The thermal conductivity of this coating layer mitigates conductive heat transfer through the wall and can result in a kiln shell temperature drop of 200–250 K [1]. Then, as heat flows past the coating layer through the refractory brick and kiln shell, the tangential variations are smoothed resulting in total tangential differences much less than those on the inside, which is why the external surface is approximated as being isothermal. Despite this fact, many production facilities offset the fans so that they are directed more closely at the tumbling particle bed, which may or may not enhance the overall heat transfer from the kiln. The purpose of this study is to consider a bank of impinging fans directed at the kiln wall at different distances from the kiln shell, different axial separation, and different lateral offsets from the kiln centerline to quantify the convective heat transfer and specifically, to understand the degradation/enhancement in heat transfer associated with offsetting the fans away from the cylinder axis. In the interest of generality, the kiln in this study is considered to be a horizontal cylinder and rotation is ignored; as mentioned above, the slow rotation only serves to make the outer surface more nearly isothermal, which is the heating condition used in this study. While there have been many studies that have considered convective heat transfer due to impinging jets and banks of jets, they have been predominantly focused on impingement on a flat plate. The most notable of these are the works of Martin [3], Jambunathan et al. [4], Zuckerman and Lior [5] and Yule [6]. In addition, the effect of turbulence on heat transfer by an impinging slot-jet on a flat plate was studied by Gardon and Akfirat [7]. Far fewer investigations of jet impingement on a circular cylinder exist in open literature, especially for cases where the jet to cylinder diameter is large.

Several studies involving impingement on a cylinder relate to impingement from slotted jets that are oriented with the axis of the cylinder. Olsson et al. [8] studied the effect of a single slot jet impinging on a single cylinder for operational parameters such as jet-to-cylinder distance, and cylinder curvature for jet Reynolds numbers (based on jet exit velocity and slot width) ranging from 23,000 to 100,000. It was concluded that average and stagnation Nusselt numbers increase with increasing jet Reynolds number and surface curvature; however, the effect of jet-to-cylinder spacing was not found to be significant. Another study by Olsson et al.

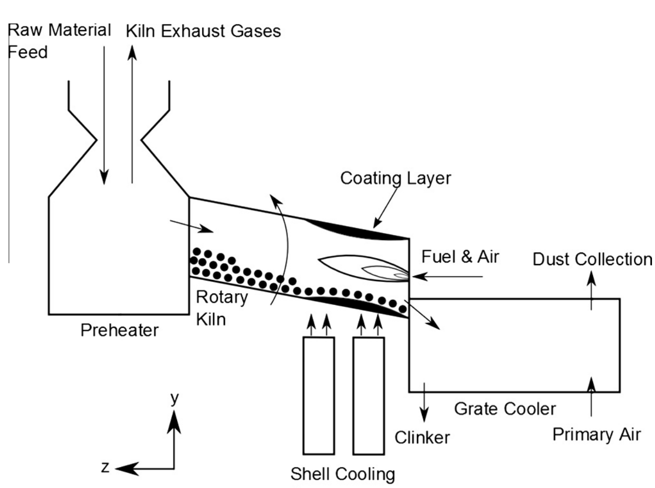

Fig. 1. Schematic of a rotary cement kiln.

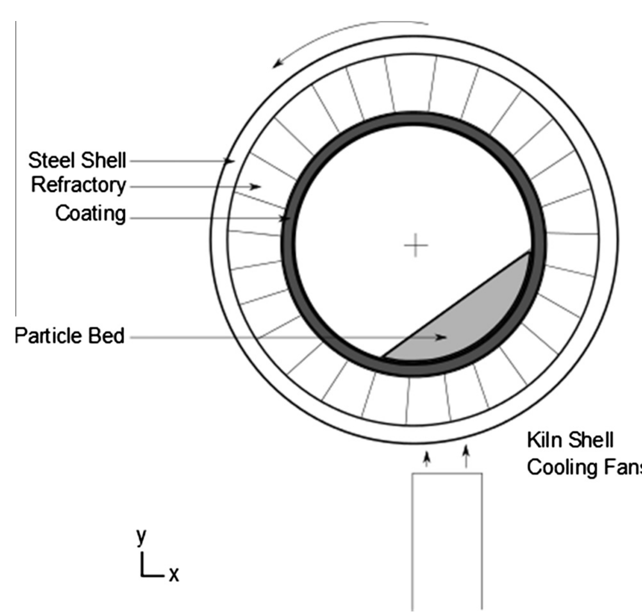

Fig. 2. Cross-section of rotary cement kiln.