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Heat Transfer Mechanisms in High-Pressure Die Casting (HPDC)

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A B S T R A C T :

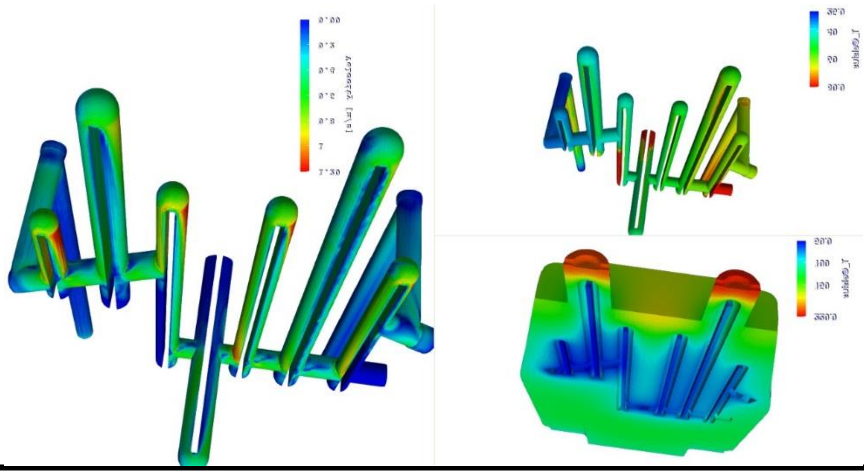
High-Pressure Die Casting (HPDC) is a widely used manufacturing process for creating complex shapes with high precision and dimensional accuracy. The process involves the injection of molten metal into a mold under high pressure. Efficient heat management during HPDC is crucial to ensure optimal solidification, minimize defects, and improve cycle times. This paper discusses the primary heat transfer mechanisms — conduction, convection, and radiation — involved in HPDC, with a focus on their roles, governing equations, influencing factors, and practical implications. The study aims to provide insights into the optimization of the HPDC process by understanding how these heat transfer mechanisms interact and affect the overall efficiency and quality of castings

Keywords:Hpdc, Thermal Balance, Solidification, Die cooling, Soldering, Casting Defects

Introduction

The HPDC process involves molten metal being injected into a mold under high pressure, where it solidifies rapidly. The efficiency of heat transfer from the molten metal to the die directly influences cycle time, product quality, and die life. Three primary modes of heat transfer — conduction, convection, and radiation — govern the thermal behavior of the system.

Understanding the roles of these mechanisms is essential for improving process control and minimizing defects like porosity, cracking, and surface imperfections. This paper explores the role of conduction, convection, and radiation in HPDC, presenting their governing equations, calculation methodologies, and implications for the die casting process.



Heat Transfer Mechanisms in HPDC

1. Conduction

Conduction is the transfer of heat through a material without any movement of the material itself. In HPDC, conduction plays a dominant role in transferring heat from the molten metal to the die.

Fourier's Law of Heat Conduction provides the basic equation to describe the heat transfer due to conduction:

$Q=-k \cdot A \cdot dT/dx$

Where:

- Q = Heat transfer rate (W)
- k = Thermal conductivity of the material (W/m·K)

- A = Cross-sectional area of heat transfer (m²)

dT/dx = Temperature gradient (K/m)

In HPDC, the molten metal (e.g., aluminum) is at a high temperature, and the die is cooler. The heat flows from the molten metal to the die via conduction. The rate of heat transfer depends on the thermal conductivity of both the molten metal and the die material, the contact area between the metal and the die, and the temperature gradient.

Calculation Example:

Assume:

The thermal conductivity of aluminum kAl=205 W/mk

The thermal conductivity of steel ksteel=50 W/mk

Cross-sectional area A=0.01 m2

Temperature difference ΔT=400 K

Die thickness dx=0.05 m

For conduction through aluminum:

QAl=−205*0.01*400/0.05=−164,000 W

For conduction through steel:

Qsteel=−50*0.01·400/0.05=−40,000 W

Thus, the rate of heat transfer through aluminum is significantly higher than through steel, influencing the die design and material selection.

2. Convection

Convection is the transfer of heat through the movement of fluids, which can either be natural or forced. In HPDC, forced convection is more relevant, as the cooling channels in the die are designed to circulate coolant (usually water or oil) to remove heat from the die.

Newton's Law of Cooling describes the convective heat transfer:

Q=h·A·(Ts−Tfluid)

Where:

h = Convective heat transfer coefficient (W/m²·K)

A = Heat transfer area (m²)

Ts = Surface temperature (K)

Tfluid = Temperature of the cooling fluid (K)

In HPDC, the efficiency of convective heat transfer depends on the coolant's properties, flow rate, and the design of the cooling channels.

Calculation Example:

Assume:

Convective heat transfer coefficient h=500 W/m²K

Surface area A=0.02 m2

Die surface temperature Ts=350 K

Coolant temperature Tfluid=300 K

The heat transferred through convection:

Q=500*0.02*(350−300)=500*0.02*50=500 W

The heat transfer through convection is directly influenced by the coolant flow rate, the thermal properties of the coolant, and the channel design.

3. Radiation

Radiation is the transfer of heat via electromagnetic waves and does not require a medium. In HPDC, radiation becomes important when the die is open or when there are exposed hot surfaces during the process.

The heat transfer by radiation is governed by the Stefan-Boltzmann Law:

Q=ϵ·σ·A·(Ts4−Tenv4)

Where:

ϵ = Emissivity of the surface (dimensionless)

σ = Stefan-Boltzmann constant =5.67×10−8 W/m²K⁴

A = Surface area (m²)

Ts = Surface temperature (K)

Tenv = Ambient temperature (K)

Calculation Example:

Assume:

Emissivity of die surface ϵ=0.8

Surface area A=0.02 m2

Die surface temperature Ts=600 K

Ambient temperature Tenv=300 K

The heat transferred by radiation:

Q=0.8*5.67×10^−8*0.02*(600^4−300^4)

This will yield a specific heat transfer rate based on the temperature difference, though radiation typically plays a smaller role in HPDC than conduction and convection.

To demonstrate thermal equilibrium in a die casting die for an ADC-12 aluminum alloy engine bracket using thermodynamic principles.

Component and Process Parameters

Casting: Automotive engine bracket (ADC-12 aluminum alloy).
Weight: 600 gm (0.6 kg).
Die Material: H13 steel (thermal conductivity, K=27.3 W/m°C
Machine Tonnage: 300 Ton.
Cycle Time: 28 seconds.
Injection Temperature (Ti): 660°C.
Ejection Temperature (Te): 430°C.
Cavity Surface Temperature: 220°C.
Cooling Medium: Water at 25°C inlet temperature.
Cooling Channel Diameter (D): 10 mm (0.01 m).
Water Flow Rate: 3 liters/minute (velocity V=0.636 m/s)

Material Properties

ADC-12 Aluminum Alloy:
Density (ρ): 2,680 kg/m³.
Specific Heat (Cp): 963 J/kg°C.
Latent Heat (LfLf): 389,000 J/kg.
Liquidus Temperature: 580°C.
Solidus Temperature: 507°C.

1. **Coolant (Water):**

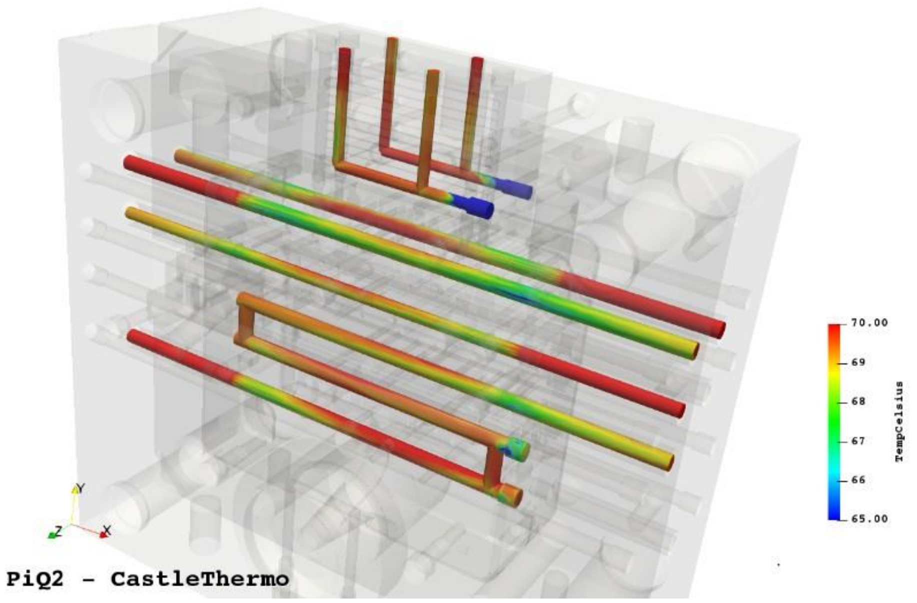
Thermal Conductivity (K): 0.58 W/m°C.
Density (ρ): 996.3 kg/m³.
Dynamic Viscosity (μ): 0.0008684 Ns/m².
Specific Heat (Cp): 4,072.7 J/kg°C.

Thermodynamic Calculations

1. Heat Load Calculation

Total heat input per cycle (Qtot):
Qs=m*Cp*(Ti−Te)=0.6*963*(660−430)=133,722 J
QL=m*Lf=0.6*389,000=233,400 J.
Qtot=Qs+QL=133,722+233,400=367,122 J.
Heat input per second (Qsec):
Qsec=Qtot/Cycle Time=367,12228=13,111 W.

2. **Heat Transfer Coefficient (h)**



Reynolds Number:

Re=V*D*ρ/μ=(0.636*0.01*996.30)/0008684=7,342.

- **Prandtl Number:**

Pr=Cp·μ/K=(4,072.7*0.00086840)/.58=6.097

- **Nusselt Number (NuNu):**

Nu=0.023·Re^0.8·Pr^0.3=0.023*(7,342)^0.8*(6.097)^0.3=68.5.

- **Heat Transfer Coefficient:**

h=Nu*K/D=(68.5*0.580)/.01=3,973 W/m²°C.

3. Cooling Channel Length (LL)

Using convection equation Q=h·A·(Ts−Tf):

A=π*D*L ⟹ L=Qsec/(h*π*D*(Ts−Tf)).

L=13,111/(3,973*π*0.01·(220−25))=2.8m

Split between moving (1.6 m) and fixed (1.2 m) sides based on heat distribution. Or we can also calculate separately for moving and fix side on the basis of volume.

4. Depth of Cooling Channels

Using conduction equation Q=(K*A*(T1−T2))/Ddepth:

Ddepth=(K*A*(T1−T2))/Qsec.

Assuming projected area A=15,000 mm²=0.015 m²:

Ddepth=27.3*0.015*(220−120)/13,111=0.0031 m=3.1 mm.

Results and Thermal Balance

- **Total Cooling Channel Length**: 2.8 m (optimized distribution).
- **Depth from Surface**: 3.1 mm (ensures uniform heat extraction).
- **Thermal Equilibrium:**

Heat input (Qsec=13,111) ≈ Heat extracted (Q=h*A*ΔT=13,111 W).

Die temperature stabilizes at 220°C, preventing soldering and porosity.

By applying thermodynamic principles, the die achieves thermal balance for the ADC-12 engine bracket. The redesigned cooling channels (2.8 m length, 3.1 mm depth) ensure efficient heat dissipation, maintaining a 28-second cycle time. This validates the original paper's methodology and demonstrates that thermal equilibrium is achievable with ADC-12 alloy under realistic HPDC conditions.

Conclusion

Heat transfer in HPDC is a complex process involving conduction, convection, and radiation. The efficiency of these mechanisms directly affects the solidification rate, cycle time, casting quality, and die life. Conduction plays a dominant role in the heat transfer between molten metal and the die, while convection is essential for cooling the die using circulating coolants. Radiation, though less significant, cannot be entirely ignored, especially when the die is open or surfaces are exposed.

The optimization of HPDC requires a careful balance between these heat transfer mechanisms, as well as considerations such as die material selection, cooling channel design, and temperature management. Understanding the equations governing these processes and the parameters affecting them is critical for improving the overall efficiency and quality of the die casting process.

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