OPTIMAL TUNDISH DESIGN METHODOLOGY

IN A

CONTINUOUS CASTING PROCESS

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ABSTRACT

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The demand for higher quality steel and higher production rates in the production of steel slabs is ever increasing. These slabs are produced using a continuous casting process. The molten steel flow patterns inside the components of the caster play an important role in the quality of these products. A simple yet effective design method that yields optimum designs is required to design the systems influencing the flow patterns in the caster. The tundish is one of these systems. Traditionally, experimental methods were used in the design of these tundishes, making use of plant trials or water modelling. These methods are both costly and time consuming. More recently, Computational Fluid Dynamics (CFD) has established itself as a viable alternative to reduce the number of experimentation required, resulting in a reduction in the time scales and cost of the design process. Furthermore, CFD provides more insight into the flow process that is not available through experimentation only. The CFD process is usually based on a trial-and-error basis and relies heavily on the insight and experience of the designer to improve designs. Even an experienced designer will only be able to improve the design and does not necessarily guarantee optimum results. In this thesis, a more efficient design methodology is proposed. This methodology involves the combination of a mathematical optimiser with CFD to automate the design process. The methodology is tested on a four different industrial test cases. The first case involves the optimisation of a simple dam-weir configuration of a single strand caster. The position of the dam and weir relative to inlet region is optimised to reduce the dead volume and increase the inclusion removal. The second *case involves the optimisation of a pouring box and baffle of a two-strand caster. In this case, the pouring box and baffle geometry is optimised to maximise the minimum residence time at operating level and a typical transition level. The third case deals with the geometry optimisation of an impact pad to reduce the surface turbulence that should result in a reduction in the particle entrainment from the slag layer. The last case continues from the third case where a dam position and height is optimised in conjunction with the optimised impact pad to maximise the inclusion removal on the slag layer. The cases studies show that a mathematical optimiser combined with CFD is a superior alternative compared to traditional design methods, in that it yields optimum designs for a tundish in a continuous casting system.*

Keywords: *tundish, continuous casting, computational fluid dynamics, mathematical optimisation, computational flow optimisation, design methodology, steelmaking, inclusion removal, tundish design*

SAMEVATTING

Titel: Optimale Gietbak Ontwerpsmetodiek van'n Kontinue-gietproses

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Daar bestaan 'n alomtoenemende aanvraag vir hoër kwaliteit staalplate wat teen 'n hoër tempo geproduseer word. Die plate word geproduseer deur 'n kontinue gietproses. Die vloeistaal patrone in die proses speel 'n belangrike rol in die kwaliteit van die produkte. 'n Eenvoudige maar tog effektiewe ontwerpsmetode word verlang wat optimum ontwerpe lewer van die sisteme wat die vloeipatrone beïnvloed. Die gietbak is een van die sisteme. Histories is eksperimentele metodes gebruik in die ontwerp van die gietbakke, met gebruikmaking van aanlegtoetse of water modellering, Meer onlangs is Berekenings Vloei Dinamika (BVD) gebruik as 'n alternatief om die aantal eksperimentele toetse te verminder en om sodoende die tydskaal en kostes van die ontwerpsproses te verminder. Verder verskaf BVD baie meer insig in die vloei proses wat nie beskikbaar is met tradisionele eksperimentele metodes nie. Die BVD proses is gewoonlik gebaseer op 'n tref-of-fouteer basis en steun sterk op die ontwerper se insig en ondervinding om die ontwerp te verbeter. Selfs 'n ontwerper met baie ondervinding sal slegs die ontwerp kan verbeter en sal nie noodwendig 'n optimum ontwerp kan gee nie. In die tesis word 'n meer effektiewe ontwerpsmetodiek voorgestel. Die metodiek behels die kombinering van 'n wiskundige optimerings program met BVD om die ontwerpsproses te automatiseer. Die metodiek word getoets op vier verskillende toetsgevalle. Die eerste geval is die optimering van 'n eenvoudige dam-keermuur konfigurasie vir 'n enkelstring gietproses. Die posisie van die dam en keermuur relatief tot die inlaat area is geoptimeer om die dooie volume verminder en die inklusie verwydering te vermeerder. Die tweede geval beskryf die optimering van die gietboks en skermplaat van 'n tweestring gietbak. In die geval *word die gietboks en skermplaat geometrie geoptimeer om die minimum residensie tyd te maksimeer by die bedryfsvlak en by 'n tipiese transisievlak. Die derde geval beskou die geometrie optimering van 'n impakstuk om die oppervlak turbulensie te verlaag, wat veroorsaak dat minder partikels in die vloei ingetrek sal word vanaf die slaklaag. Die laaste geval volg op geval drie waar 'n dam se posisie en hoogte geoptimeer word saam met die geoptimeerde impakstuk om die inklusie verwydering op die slaklaag te maksimeer. Die toetsgevalle wys dat 'n wiskundige optimeerder gekombineerd met BVD 'n beter alternatief is as tradisionele ontwerpsmetodes, om sodoende optimum ontwerpe van 'n gietbak van 'n kontinue stringgiet proses te lewer.*

Sleutelwoorde: *gietbak, stringgiet, berekenings vloei dinamika, wiskundige optimering, berekenings vloei optimering, ontwerpsmetodiek, staalmaak, inklusieverwydering, gietbak ontwerp*

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NOMENCLATURE

Symbols:

Variable	**Description**	**Unit**
a_1, a_2, a_3	Constants for particle drag law	-
$\boldsymbol{A}$	Approximated Hessian matrix	-
a	Approximated curvature	-
C_D	Particle drag coefficient	-
C_L	Constant for eddy lifetime	-
C_μ	Empirical constant for k-ε turbulence model	-
C_1	Empirical constant for k-ε turbulence model	-
C_2	Empirical constant for k-ε turbulence model	-
c_p	Specific heat at constant pressure	J/kg·K
D_{eff}	Local effective diffusion coefficient	m^2/s
D_0	Laminar diffusion coefficient	m^2/s
D/Dt	Substantial derivative	-
d_p	Particle diameter	M
E	Empirical constant for the wall function in turbulent flow	-
f	Objective function	♦
Fr	Froude number	-
g	Gravitational acceleration	m/s^2
g_j	j-th inequality constraint	♦
H	Fluid enthalpy	J/kg
H	Hessian matrix	-
h_k	k-th inequality constraint	♦
$\boldsymbol{I}$	Identity matrix	-
K	Thermal conductivity	W/m·K

♦ Problem dependant

Variable	Description	Unit
k	Turbulent kinetic energy	m^2/s^2
k_P	Turbulent kinetic energy at point P	m^2/s^2
L	Reference length	m
	Turbulent length scale	m
L_e	Eddy length scale	m
m	Number of inequality constraints	-
n	Number of design variables	-
$\overline{p}$	Time-averaged pressure equations	Pa
p	Pressure	Pa
	Penalty function	-
	Number of equality constraints	-
Re	Reynolds Number	-
Sc_t	Turbulent Schmitt number	-
S_m	Mass source	$kg/m^3 \cdot s$
t	Time	s
t_{cross}	Particle eddy crossing time	s
T	Temperature	K
T_0	Reference temperature	K
U	Reference velocity	m/s
u	Velocity in x-direction	m/s
U^*	Dimensionless velocity	-
u_i	Instantaneous velocity in the i-th direction	m/s
U_i	Mean velocity in the i-th direction	m/s
u_i'	Fluctuating part of velocity in the i-th direction	m/s
U_P	Mean velocity of the fluid at point P	m/s
u_p	Particle velocity	m/s
$\overline{\mathbf{V}}$	Time-averaged velocity vector	m/s
$\mathbf{V}$	Velocity vector	m/s
v	Velocity in y-direction	m/s
V_{dpv}	Dispersed plug volume	-
V_{dv}	Dead volume	-
V_{mv}	Well-mixed volume	-

Variable	**Description**	**Unit**
V_{pv}	Plug flow volume	-
v_t	Eddy viscosity	m²/s
w	Velocity in z-direction	m/s
x	Distance in x-direction	m
$\boldsymbol{x}$	Design variable vector	♦
$\boldsymbol{x}^*$	Optimum design variable vector	♦
x_i	Spatial co-ordinate in the i-direction	m
	i-th design variable	♦
y	Distance in y-direction	m
Y	Inclusion mass fraction	-
y^*	Dimensionless distance fro the wall	-
y_P	Distance from point P to the wall	m
z	Distance in z-direction	m
α	Penalty function parameter for inequality constraint	-
β	Thermal expansion coefficient	1/K
	Penalty function parameter for equality constraint	-
γ	Penalty function parameter for objective function	-
δ_i	Move limit on i-th design variable	♦
δ_{ij}	Kronecker delta function	-
ε	Turbulent dissipation rate	m^2/s^3
ζ	Normally distributed random number	-
θ_{av}	Average residence time	-
θ_{min}	Minimum break-through time	-
θ_{peak}	Time to reach peak concentration	-
κ	Von Kármán constant	-
λ	Bulk viscosity	m/s^2
μ	Kinematic viscosity	m^2/s
	Large positive number	-
ρ	Density	kg/m^3
	Penalty function parameter	-

♦ Problem dependant

Variable	Description	Unit
ρ_0	Reference density	kg/m^3
ρ_p	Particle density	kg/m^3
σ_ε,	Empirical constant for k-ε turbulence model	-
σ_k,	Empirical constant for k-ε turbulence model	-
τ	Theoretical residence time	-
	Particle relaxation time	-
τ_e	Characteristic lifetime of an eddy	s
ω	Turbulent vorticity	1/s
Δx_{norm}	Normalized step size	-
Δf_{norm}	normalized change in function value	-
Δx_i	Step size for i-th design variable	♦
Φ	Viscous dissipation	W/m^3

Abbreviations:

CFD	Computational Fluid Dynamics
RANS	Reynolds Averaged Navier-Stokes equation
RTD	Residence time distribution
MRT	Minimum residence time
RSM	Reynolds Stress Models
ASM	Algebraic Stress Models
LES	Large-Eddy Simulation
DNS	Direct Numerical Simulation
SEN	Submerged Entry Nozzle

♦ Problem dependant