A contribution to the correct use of heat transfer coefficients and cooling media properties in simulation of foundry processes

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HEAT TRANSFER COEFFICIENTS

Wide literature
Data sometimes contradictory

interface	**HTC (W/m^{2}K)**	**notes**	ref.
Al-copper chill	HTC(t): 2000-200	interface gap	1
Al-copper chill	HTC(t): 2000-1000	interface contact	1
Al4.5Cu-metal chill	1900-2200	interface contact	2
Al-copper chill	1200		6
Al-copper chill	1750	suggestions for HTC = HTC(T)	6
Al4.5Cu-steel chill	4400	polished steel, thickness = 1mm	7
Al4.5Cu-chill	2000	perfect chill	7
Al-copper chill	HTC(t): 1500-200		11
AlSi-copper chill	HTC(t): 2000-500	roughness, composition	12
Al alloys-steel die	1150		3
Al4.5Cu-metal mold	420		4
AlCu-steel mold	1900	coating (0.1mm)	7
AlSi-brass	HTC(t): 2000-500	roughness, composition	12
AlSi-steel	HTC(t): 2000-500	roughness, composition	12
AlSi-cast iron	HTC(t): 2000-500	roughness, composition	12
Al4.5Cu-sand mold	42		4
cast iron-sand mold	334.9		5
steel-sand mold	20.9		9
iron-iron mold	500	imperfect contact	10
iron-iron mold	1000	perfect contact	10
mold-air	42		8
sand mold-air	6.8		5
bronze-copper chill	HTC(t): 1500-100	interface gap	1
bronze-copper chill	HTC(t): 2000-1000	interface contact	1
Mg-chill	1046		8
Mg-mold	418		8
copper-sand	HTC(t): 200-500	perfect contact	11
copper-sand	HTC(t): 200-450-200	air gap	11

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⇒ SENSITIVITY ANALYSES ARE STRONGLY NEEDED

HTC Constant

or

HTC function of temperature or time

other variables: alloy, die, operative configuration

Equipments for HTC measurements (end-chill experiments)

From experimental data to simulation

Sensitivity analysis carried out by Overfelt:
evaluation of the errors
due to uncorrect values of some input data

Data on HTC alloy-mold

...but some guidelines are also needed
for the cooling media and
for their heat transfer coefficient (hi) with the mold

Simulation of casting process
Analysis of sensitivity of solidification model

Simulations have been carried out on MAGMAsoft, changing

- HTC alloy-mold
- hi cooling medium-mold
- kind of cooling medium

Test configuration:

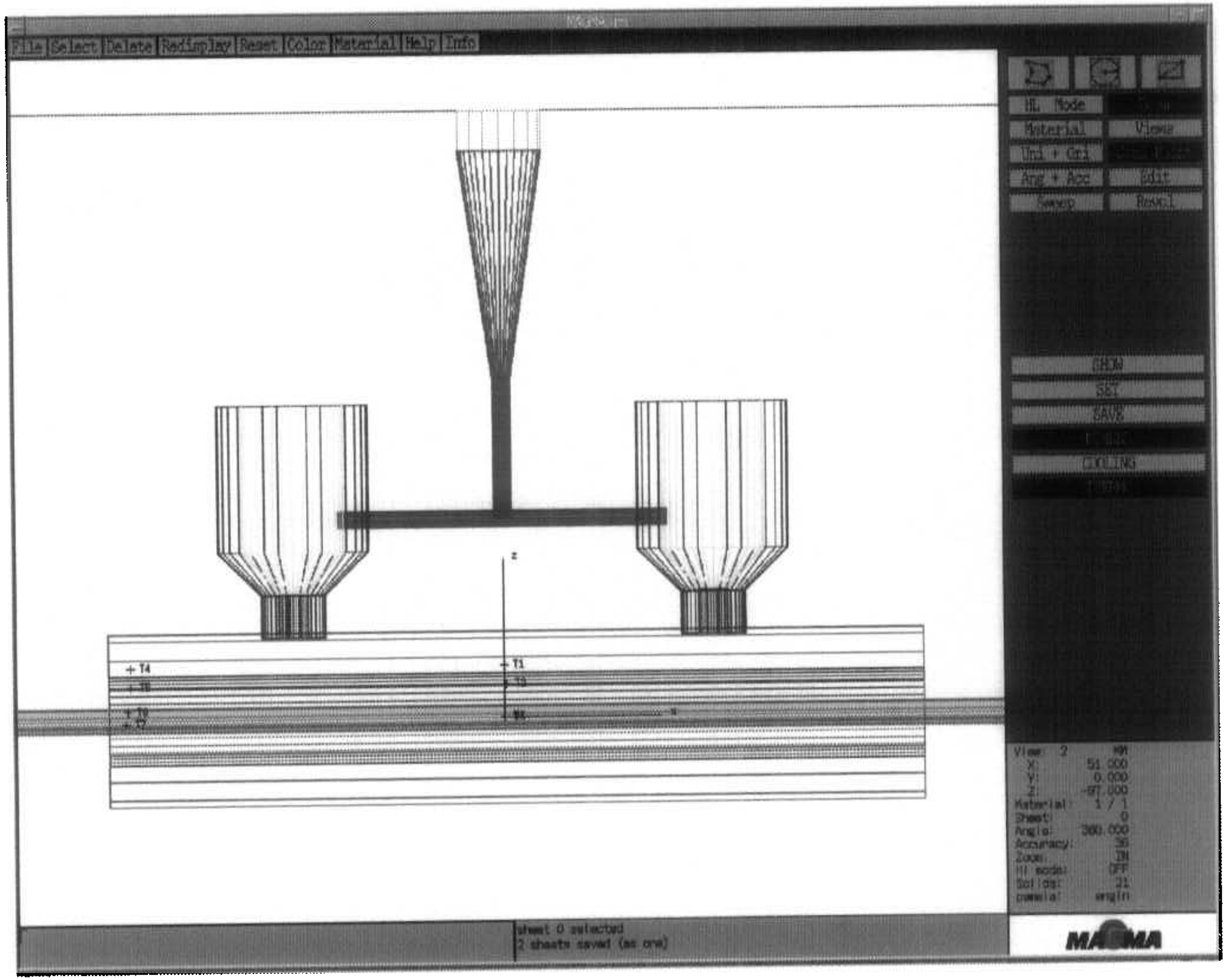
tube
internal diameter = 12 mm,
external diameter = 20 mm,
length = 400mm

two feeders
core

6 "T control points", (casting, core, cooling medium)

not a "real" casting

Geometric configuration



<u>Materials</u>

- steel (die, core),
- A356 (casting).

<u>3 cooling media:</u>

- CoolMed (as defined by MAGMAsof),
- water
  (various starting temperatures and speed = constant =1 m/s),
- air (various starting temperatures, speeds and pressures)

<u>Properties of fluids:</u>

- density,
- themal conductivity,
- specific heat.

T = 20°C:

	medium		
	CoolMed	water	air
density (kg/m^3)	1000	997	1.198
thermal conductivity (W/mK)	1000	0.599	0.0262
specific heat (J/kgK)	1.0 x 10^9	4180	1042

The cooling fluid in MAGMAsoft:

MAGMAsoft considers the <u>cooling fluid</u> as a <u>material</u>
(convection and heat transfer are not directly evaluated)

Simulation of casting process
Analysis of sensitivity of solidification model

Evaluation of heat transfer coefficient
between cooling fluids and mold

Approach: heat transfer in a tube (see theory on heat exchangers)

hi = f' ### c v $Pr^{-2/3}$

where
f' = experimental coefficient = $1.86\ Re^{-2/3}\ (d/L)^{1/3}$ [laminar flow]
= $0.027\ Re^{-0.2}$ [turbulent flow]
= density (kg/m^3)
c = specific heat (kcal/kgK)
v = speed (m/s)
Pr = Prandtl number = $3.6c\mu/\lambda$
μ = viscosity (cp)
λ = thermal conductivity (kcal/mhK)
Re = Reynolds number= $(\rho v d/\mu)$
d = diameter of the tube (mm)

hi in $kcal/m^2hK$, then conversion to W/m^2K.

Effect of temperature
Effect of working conditions (pressure, speed...)

...however, hi is not an exact value
(pressure oscillations, oxidation phenomena, fouling factors...)

Analysis approach:

- behaviour of the system keeping the cooling medium (CoolMed) constant and changing hi;

- effect of various cooling media on the thermal model results

- effect of errors or changes in HTC

Analysis parameters

- thermal cycle of the die (Tp = peak temperature, tp = time for obtaining Tp);

- maximum temperature calculated for the cooling medium (Tmref)

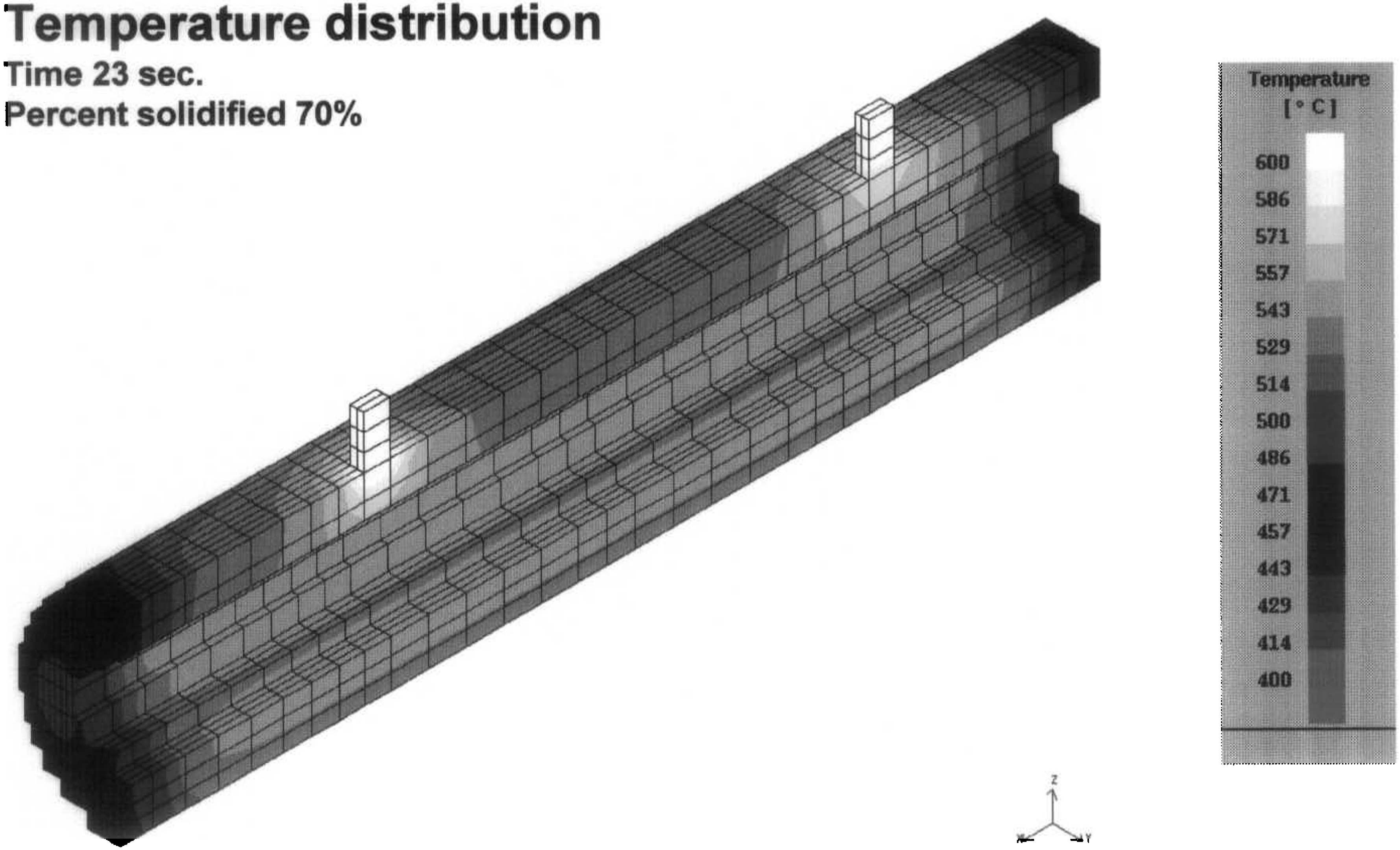
- time-temperature diagrams for the alloy, the die and the cooling medium;

- local solidification times (from "solid criterion" option).

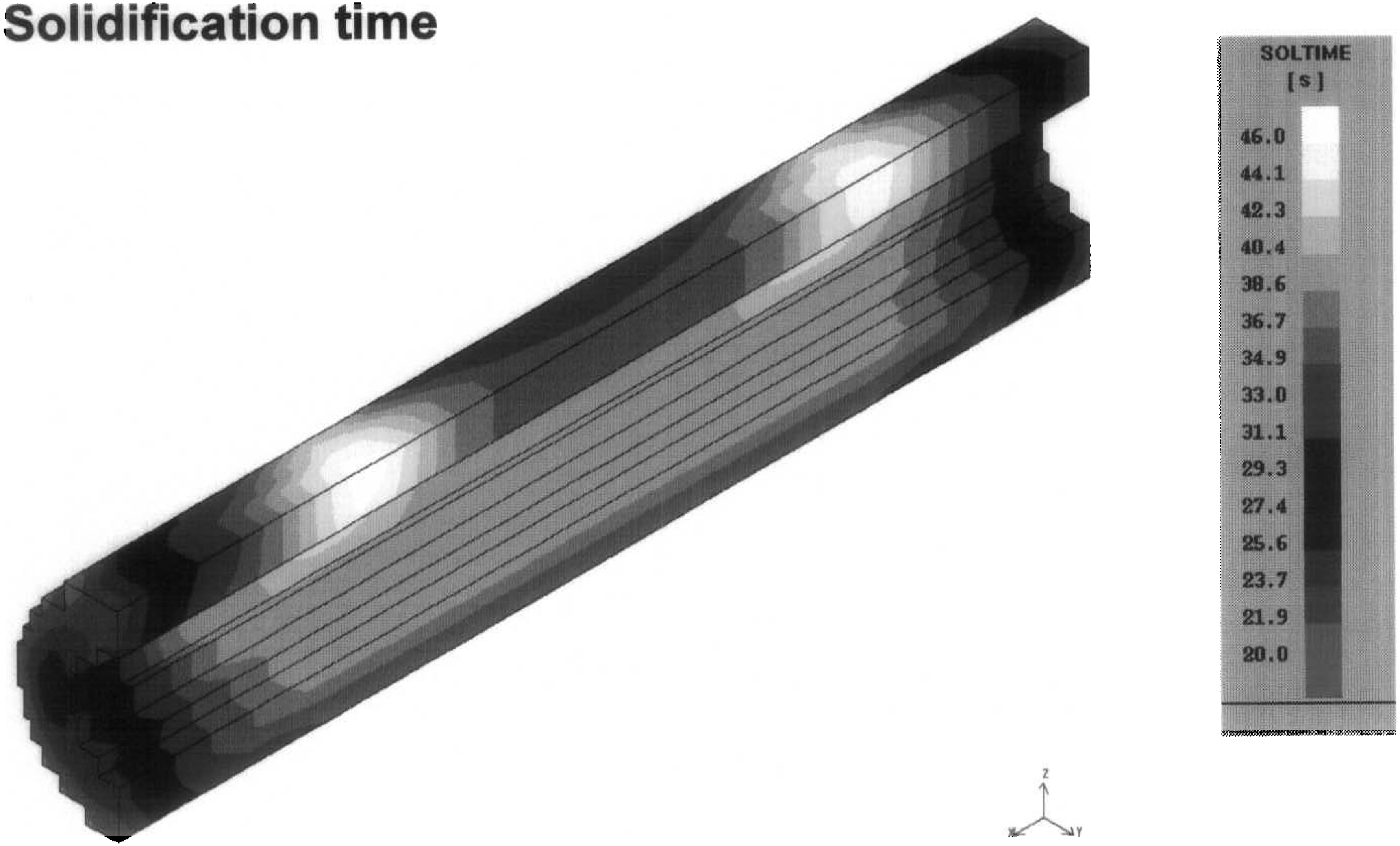
Temperature distribution

Time 23 sec.

Percent solidified 70%



Solidification time



RESULTS

The CoolMed and hi

- the cooling medium is a material

- it has to remove heat from the system mold + casting
during the process it is continuously renewed, to perform this effect (as an example, in continuous casting an increase of 8-11°C has been measured in cooling water);

- the "ideal" cooling medium must remove heat without increasing too much its temperature

- this result can be achieved under the hypotheses of high thermal conductivity (efficient heat removal and temperature homogeneity), high density and specific heat (to assure limited temperature increases): i.e. by means of the CoolMed

- the "fictitious" properties of CoolMed are aimed at realistically simulating the behaviour of a cooling fluid by means of a "static" material

- the use of "real" cooling fluids, such as water or air, can be simulated by means of CoolMed, correctly evaluating the heat transfer coefficient hi at the mold-CoolMed interface

In the above described configuration, some simulations have been performed using the CoolMed (T = 30°C) with various values of hi:

- 1000 W/m^{2}K (air at 20°C, 5 atm and 50 m/s);

- 4000 W/m^{2}K (water at 25°C e 1m/s);

- 6970 W/m^{2}K (water at 80°C e 1 m/s).

RESULTS

The CoolMed and hi

	hi (W/m^2K)	Tp (°C)	tp (s)	Tmref (°C)
CoolMed	1000	339	31	30
	4000	303	31	30
	6970	290	31	30

Comparison among the simulations performed
considering different values of the heat transfer coefficient
between mold and cooling fluid

Efficiency of CoolMed

tp is constant: the heating times of the mold are not affected by changes in hi

The maximum temperature reached by the mold changes:

339°C when the heat transfer is not very good
(hi = 1000 W/m^2K)
290°C when the heat transfer is excellent (hi = 6970 W/m^2K)

A difference of 50°C is very important in terms of thermal fatigue and mold life

However, limited errors (a few percent) in the evaluation of hi do not affect too much the final results.

Similar considerations can be done for local solidification times

RESULTS

Effect of cooling fluid properties

The use of water and air (with their true termophysical properties) as cooling fluids does not lead to reliable results: the continuous re-generation of the cooling fluid is not taken into account.

Let's consider hi = constant = 4000 W/m^2K, and compare the different cooling media.

	hi (W/m^2K)	Tp (°C)	tp (s)	Tmref (°C)
Water	4000	370	32	105*
Air	4000	366	32	366
CoolMed	4000	303	31	30

Comparison among the different cooling fluids
(* value at the end of simulation, but not yet the maximum one)

- the cooling given by air and water can not be appreciated;
- the mold becomes hotter then the casting;
- the maximum temperatures of the mold are higher (+70°C) than those calculated using the CoolMed;
- the water rises its temperature (boiling, so drop of the heat transfer efficiency);
- the air, rises its temperture up to about 370°C, and consequently increases its pressure (PV = nRT !)
- a hi = hi (T) function should be introduced.

The use of "true" air and water is not significant and not realistic, while CoolMed works very well (only some cautions must be observed)

RESULTS

Improving the use of cooling fluid in simulation

The CoolMed overstimates the effect of the cooling fluid: no temperature increases is usually calculated
This is not strictly true (cooling fluid: + 10-15°C)

Some cooling fluids having properties ranging from water/air to CoolMed can be studied:

REFR1:

density and thermal conductivity similar to water (ρ = 1000 kg/m^3, λ = 0.5 W/mK), while Cp = 1 x 10^5 J/kgK

REFR2:

density similar to water (ρ = 1000 kg/m^3), with intemediates thermal condctivity and specific heat (λ = 100 W/mK, Cp = 1 x 10^6 J/kgK)

REFR3:

properties between water and CoolMed: ρ = 100 kg/m^3, λ = 100 W/mK, Cp = 1 x 10^4 J/kgK

RESULTS

Improving the use of cooling fluid in simulation

REFR1:
Increase in temperature of about 12-13°C
The use of the thermal conductivity of water does not take into account the heat removal due to the continuously changing cooling fluid
The maximum temperature of the die is constant and overstimated The time for achieving Tpeak is constant.

REFR2:
An increase in thermal conductivity is associated with acceptable temperature increases in the mold and with a 20°C heating of the refrigerant itself

REFR3:
Similar results are achieved; the lower specific heat makes lower the temperature increase of the refrigerant itself.

	hi (W/m^2K)	Tp (°C)	tp (s)	Tmref (°C)
Refr1	1000	354	32	43*
Refr1	4000	354	32	43*
Refr1	6970	352	32	42*
Refr2	4000	305	31	50*
Refr3	4000	308	26	33*
CoolMed	4000	303	31	30

Comparison among the "intermediates" cooling fluids
(* value at the end of simulation, but not yet the maximum one)

RESULTS

SENSITIVITY of the MODEL to HTC variations

Simulations parameters:

A356, cast at 700°C
Mold = steel (30°C)
Coolmed (30°C)
Insulation

HTCs: CoolMed - Mold = C1000
Insulation - Casting = 0.001 (W/m^2K)
Insulation - Mold = 0.001 (W/m^2K)

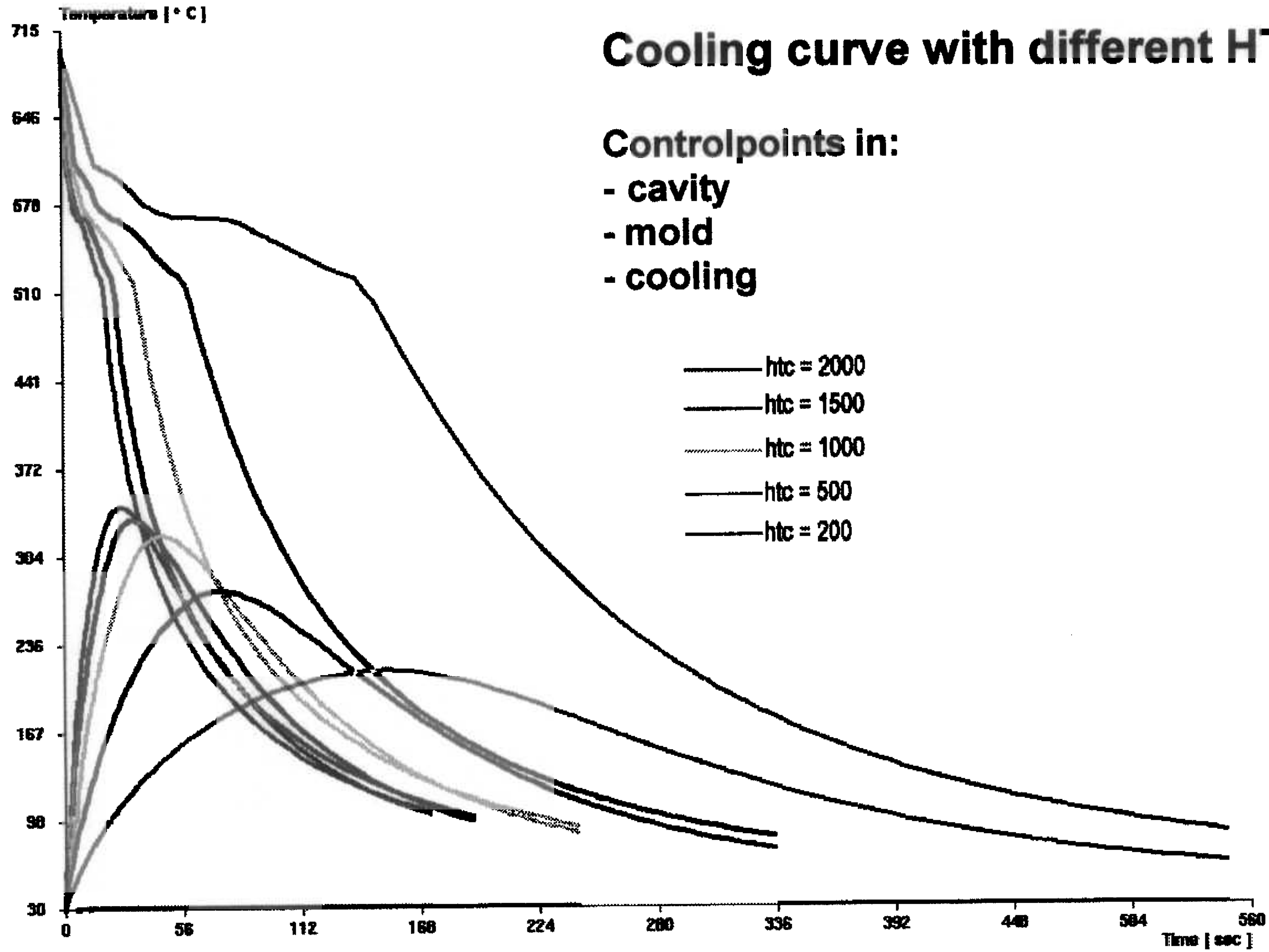
Solver = 3, solidification stopped at 507°C

HTC casting-mold: 200 - 500 - 1000 - 1500 - 2000 (W/m^2K)

Simulation of casting process
Analysis of sensibility of solidification model

Cooling curve with different HTC

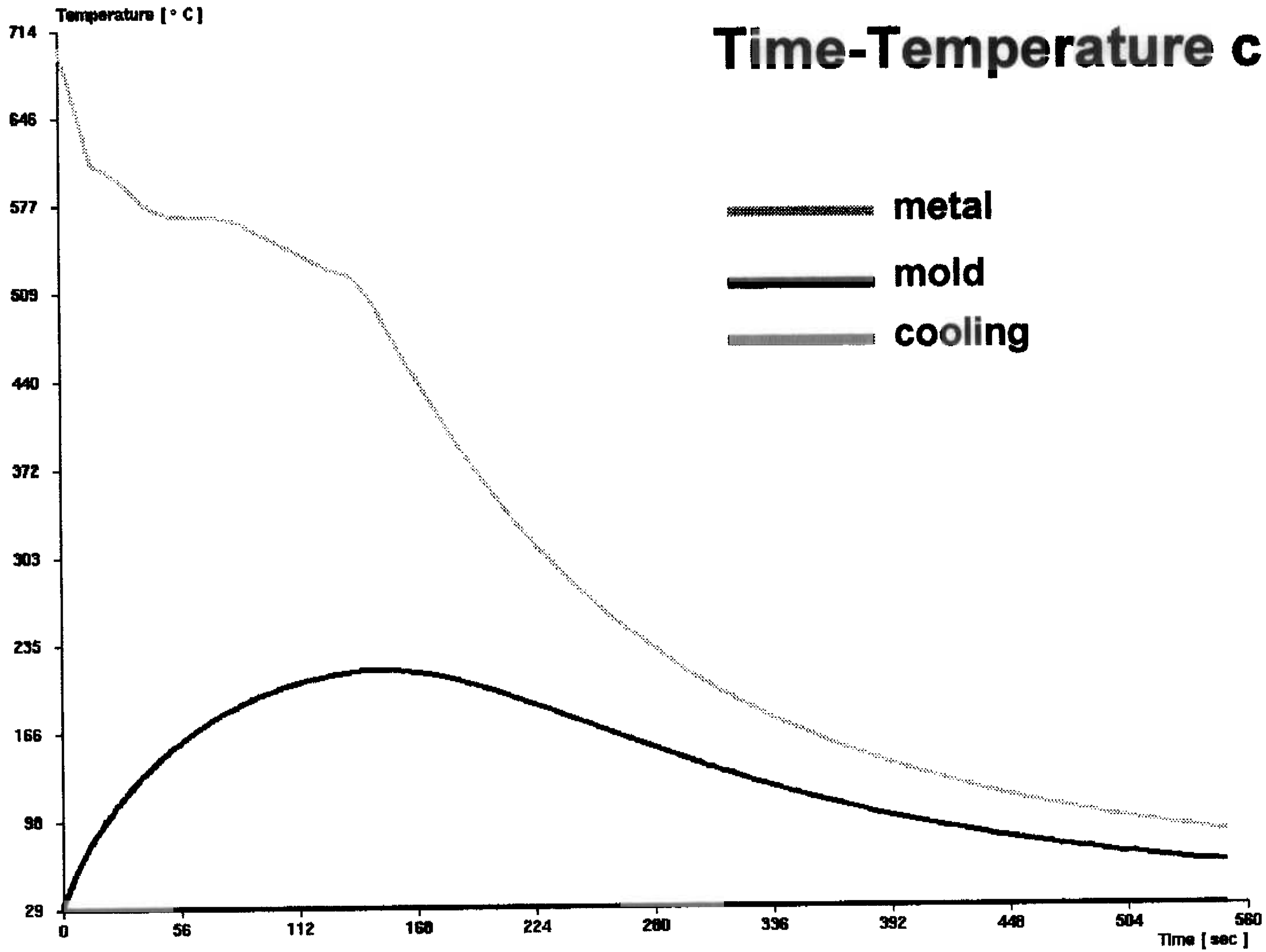
Controlpoints in:
- cavity
- mold
- cooling



ENGIN SOFT

Simulation of casting process
Analysis of sensibility of solidification model

Time-Temperature curve

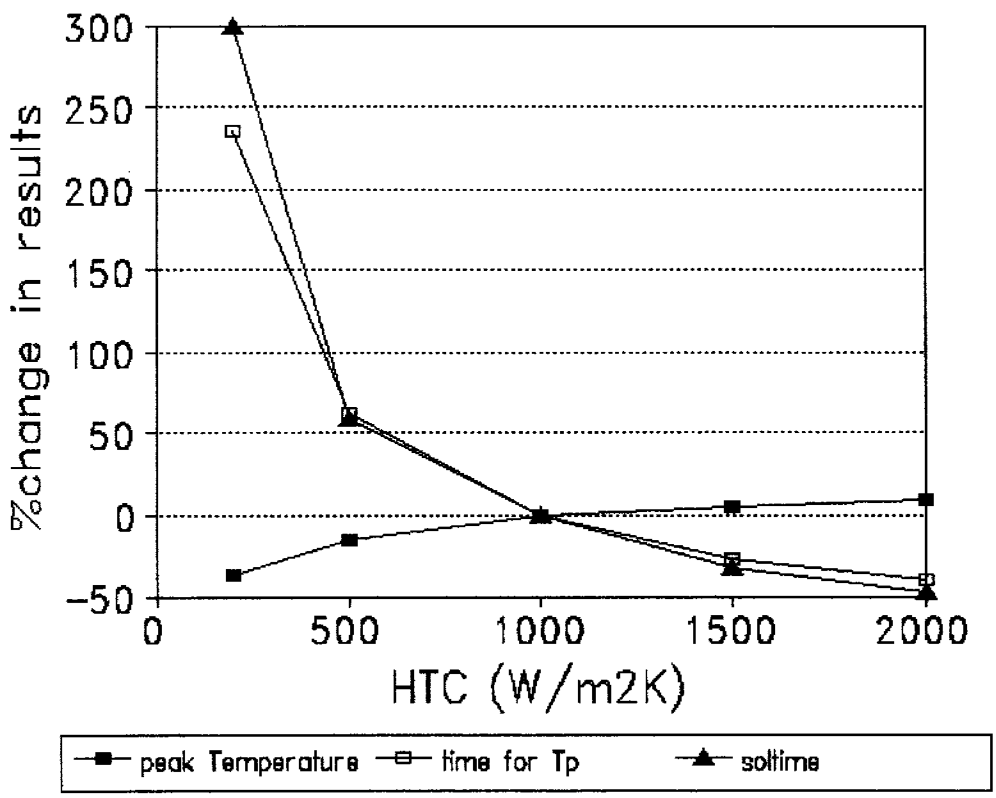


RESULTS

<u>SENSITIVITY of the MODEL to HTC variations</u>

values	HTC (W/m^2K)	Tp (°C)	tp (s)	soltime (s)
A356 CoolMed	200	184	151	137
	500	248	73	54
	1000	292	45	34
	1500	306	33	23
	2000	317	27	18

%change A356 CoolMed	HTC	Tp	tp	soltime
	200	-37%	+235%	+303%
	500	-15%	+62%	+59%
	1000	0	0	0
	1500	+5%	-27%	-32%
	2000	+9%	-40%	-47%



CONCLUSIONS

A proper variation of thermophysical properties of the cooling fluid allows a proper simulation of the heating of the cooling fluid itself during the process.

Using a correct law hi = hi(T) for the heat transfer cooling fluid-mold, a more accurate simulation of the thermal fields and of the process is possible.

The characteristics of the real system (cooling-mold-casting) will suggest the more adequate "corrections" of the cooling fluid properties.

The uncorrect evaluation of HTC (alloy-mold) may lead to significant errors in terms of mold thermal field prediction. More dramatic errors are produced in soltime calculations and, consequently, in microstructural predictions.