GENERAL

The calculation of the total energy content of a molten polymer is fairly simple. However, calculations regarding the distribution/dissipation of that energy during a moulding cycle are complex and, as a result, usually neglected. The design of the cooling circuit is therefore often left to the intuition/experience of the tool designer. Whether or not the tool subsequently runs satisfactorily is then largely a matter of luck. These Technical Notes are a simplified guide to the calculations when using Cool Pipes and will give a degree of assurance that a suitable Cool Pipe has been selected.

There are a number of dynamic variables that complicate the calculations and these include:

1. The specific heat of the polymer (temperature dependent),

2. The latent heat of fusion of the polymer (where applicable),

3. The heat losses/gains to the injection moulding machine and surrounding air,

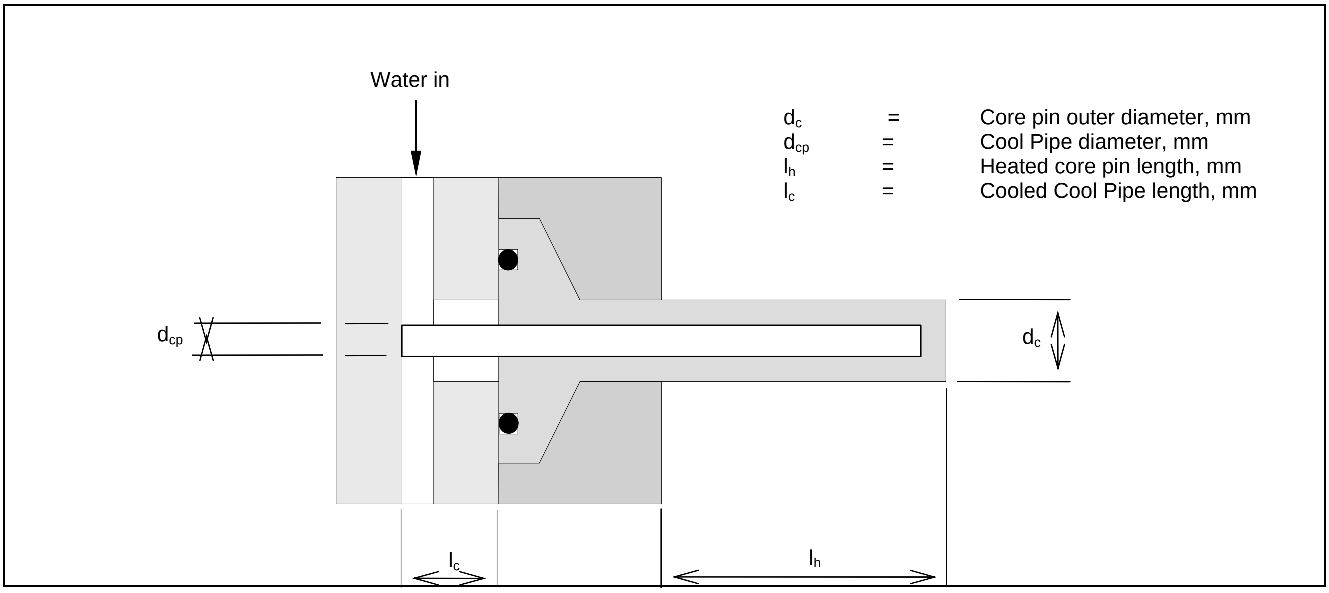
4. The surface coefficient of heat transfer between the coolant and the cooled areas of the tool,

5. The temperature and/or heat flow profile through the polymer and core into the coolant.

The dynamic nature of these and other variables makes absolute prediction of the cooling time virtually impossible. However, an accurate indication of the suitability of a Cool Pipe in a given situation can be achieved by following these notes.

OVERVIEW

These guidance notes are based on the following representational example;



The following procedure is adopted:

1. Calculate the total heat content of the polymer that must be removed,
2. Calculate the necessary heat energy extraction rate for a given cycle time,
3. Calculate the cycle average Cool Pipe temperature under condition 2. above,
4. Determine the heat transport capability of the Cool Pipe at its operating temperature,
5. Compare 2 and 4 above to confirm that the Cool Pipe will be operating within its limits,
6. Calculate the minimum necessary length of the Cool Pipe to be cooled.

1. POLYMER TOTAL HEAT CONTENT TO BE REMOVED

In practice, in a typical application, only some 70% of the total heat content is dissipated through the core - the remainder is lost via the cavity, etc.. For a 'worst case' calculation, it is safest to assume that the total energy content will be removed via the core and this is the approach adopted by these notes.

If;

m	=	Component weight,	gm
T_1	=	Polymer injection temperature,	^oC
T_2	=	Component ejection temperature,	^oC
l_f	=	Latent heat of fusion of the polymer (crystalline only),	$J\ gm^{-1}$
c	=	Specific heat capacity of the polymer,	$J\ gm^{-1}\ {}^oC^{-1}$
C	=	Heat content (to be removed),	J

then the total heat content to be removed in Joules is given by;

CRYSTALLINE POLYMERS; $C = m\,[(T_1 - T_2)c + l_f]$ J.

AMORPHOUS POLYMERS; $C = m\,(T_1 - T_2)$ J.

The figure for latent heat of fusion can be hard to obtain and it is therefore included, along with figures for T_1, T_2 and c for some of the more common polymers at the end in Appendix 1.

It is interesting to note that, where crystalline polymers are concerned, the latent heat of fusion (l_f) typically accounts for about 1/3 of the total heat energy that must be removed. Its removal does not result in any change in temperature of the component, but converts the liquid polymer into a solid.

The energy content given by the above formula is the total to be removed from the component and, as mentioned earlier, these notes assume that it is this total energy which must be removed by the Cool Pipe.

2. REQUIRED HEAT EXTRACTION RATE

If;

C	=	Heat content (to be removed)	J
t	=	Design cycle time	s
Q	=	Heat extraction rate,	W

then the heat energy removal rate necessary to achieve the design cycle time is given by;

HEAT EXTRACTION RATE; $Q = \dfrac{C}{t}$ W

3. CYCLE AVERAGE COOL PIPE TEMPERATURE

The heat transport capability of a Cool Pipe is temperature dependent. It is therefore first necessary to establish its temperature of operation before determining how rapidly the Cool Pipe will remove heat energy from the polymer. For the purpose of these Technical Notes, the calculation of the Cool Pipe temperature is based on the required heat extraction rate given by 2. above., the temperature gradient through the core pin, the temperature gradient through the core pin/Cool Pipe interface and the polymer injection/ejection temperatures.

Heat extraction rate;

Let;

Q = Heat extraction rate W (given by 2. above).

Core pin temperature gradient;

If;

δT_c	=	Core pin temperature gradient,	^oC
d_c	=	Core pin outer diameter,	mm
d_{cp}	=	Cool Pipe diameter,	mm
l_h	=	Core pin length in contact with the molten polymer,	mm
λ	=	Thermal conductivity of the core material (see appendix 2),	W m^{-1} $^oC^{-1}$

then the core pin temperature gradient is given by;

$$\delta T_c = Q\left[\frac{\log_e\left(\frac{d_c}{d_{cp}+0.2}\right)}{2\pi l_h \lambda}\right]10^3 \quad {}^oC$$

Core pin/Cool Pipe interface temperature gradient;

If;

δT_i	=	Core pin/Cool Pipe interface temperature gradient,	^oC
d_{cp}	=	Cool Pipe diameter,	mm
l_h	=	Core pin length in contact with the molten polymer,	mm

then the interface temperature gradient is given by;

$$\delta T_i = Q\left[\frac{\log_e\left(\frac{d_{cp}+0.2}{d_{cp}}\right)}{18\pi l_h}\right]10^3 \quad {}^oC$$

Injection/ejection temperatures;

Let;

T_1	=	Polymer injection temperature,	^oC
T_2	=	Component ejection temperature,	^oC

Cool Pipe average temperature;

If;

T_{AV} = Cool Pipe average temperature,

Then;

AVERAGE COOL PIPE TEMPERATURE; $T_{AV} = \left(\frac{T_1 + T_2}{2}\right) - \left(\delta T_c + \delta T_i\right) \quad {}^oC$

4. COOL PIPE HEAT TRANSPORT CAPABILITY

Table 1 below gives the heat transport capabilities of different diameter Cool Pipes at different temperatures. From the table, select the appropriate Cool Pipe diameter and the nearest temperature **below** the cycle average Cool Pipe temperature and read off the cooling capacity.

	Cooling Capacity, Watts				
Dia.mm.	25°C	50°C	100°C	150°C	200°C
2.0	9	11	14	15	14
2.5	13	16	20	22	20
3.0	18	23	28	31	28
4.0	36	42	48	53	48
5.0	57	66	76	82	76
6.0	69	80	92	99	92
8.0	96	111	128	138	128
10.0	122	142	163	177	163
12.0	150	175	202	218	202
15.0	205	240	275	300	275
20.0	275	320	370	395	370

COOL PIPE HEAT TRANSPORT CAPABILITY; Q_{cp} W

5. REQUIRED/ACTUAL HEAT TRANSPORT COMPARISON

If Q_{cp} from 4 above is greater than or equal to Q from 2. above, then the chosen diameter Cool Pipe, d_{cp} is acceptable and step 6. below should be checked.

If Q_{cp} from 4 above is less than Q from 2. above, then either;

a) The chosen Cool Pipe diameter, d_{cp}, must be increased until $Q_{cp} = Q$, or,

b) The design cycle time, t, must be increased until $Q = Q_{cp}$.

6. COOL PIPE COOLED LENGTH

The rate of transfer of heat energy from the Cool Pipe surface into the cooling water is dependent upon a number of factors. These include the velocity of the cooling water over the Cool Pipe surface and the tool geometry around the cooled section of the Cool Pipe. Precise calculation of the necessary length of the Cool Pipe to be cooled is, therefore, complex. Acceptably accurate results may, however, be obtained as follows;

Let;

Q	=	Heat extraction rate,	W
T_{AV}	=	Cool Pipe average temperature,	°C
T_W	=	Cooling water temperature,	°C
d_{cp}	=	Cool Pipe diameter,	mm
l_c	=	Minimum necessary cooled Cool Pipe length,	mm

then the minimum necessary cooled Cool Pipe length is given by;

MINIMUM COOLED COOL PIPE LENGTH; $l_c = \dfrac{42.44Q}{d_{cp}(T_{AV} - T_W)}$ mm