Novel Energy Reduction and Capital Optimisation for Rotomoulding
NERCOR
DTI Project No. 3530
Techno-economic and Process Models
Report 1

Summary

This is a preliminary report focussing on the model frameworks for which the experimental side will provide specific data.

The accepted projected proposal (dated 21 February 2007) envisages possible modifications to the standard rotomoulding process designed to increase the rate of heat transfer to and from the mould. This report shows how the effect of two of these modifications can be quantified.

1 Introduction

The four modifications referred to in the summary are:

(1) Introducing fins on to the outer surface of the mould, to increase the effective heat transfer area.

(2) Adding cartridge heaters to the mould to supplement air heating.

(3) Incorporating phrase-change materials (PCMs) in the air streams within the oven to increase the cooling process.

(4) Flow shaping to increase the heat transfer by increasing air velocities parallel to the mould surface.

Each of these four modifications needs to be quantified in terms of changes in heat transfer rate in the heating and cooling parts of the cycle. In addition, there are two overall process aspects which govern the financial and energy economics of the process, viz:

(1) Cost (c) of the modifications and their effect on throughput (Q) and thus plant economics.

(2) Energy usage (E) as may be affected by changes to the overall process of burner, oven, hot and cool air flows.

2 Starting Point: Overall Manufactured Cost Equation

The cost (c) of a unit of product is given(Ref 1) by

$$c = (r - s)/\eta + s + u/\eta + (\ell + f + \beta C)/Q \qquad (1)$$

where

r = raw materials cost per unit made (£)

s = scrap credit for rejected artefacts per unit (£)

η = conversion efficiency = units accepted for sale ÷ units made

u = utilities cost per unit made (£)

ℓ = fixed labour cost associated with plant (£ per annum)

f = fixed overheads associated with plant (£ per annum)

$\beta = i + m + d \quad (yr^{-1})$

i = interest cost of capital (yr^{-1})

m = maintenance cost of capital (yr^{-1})

d = depreciation (replacement or repayment) allowance for capital (yr^{-1})

C = original cost of equipment (£)

Q = annual output of units accepted for sale (yr^{-1})

2.1 Raw Material Cost per unit made (r)

$$r = \rho V(1 + e)c_m \qquad (2)$$

where ρ = mean density of material as made $\left({}^{kg}\!/\!{}_{m^3} \right)$

V = Volume of artefact (m^3)

e = fraction of material used which is (edge) trim or similar

c_m = cost of purchased raw materials (£/kg) (includes additives, e.g. pigments)

2.2 Utilities Cost per unit made (u)

$$u = (Ee_i + Gg_i + Hh_i + Ww_i)/Q \qquad (3)$$

where E, G, H, W are annual usages of electricity, gas, water and waste disposal services respectively and ei, gi, hi, wi are their respective unit costs.

2.3 Fixed Costs

These are represented by the term $(\ell + f + \beta C)/Q$ in equation (1).

- Labour costs (ℓ) include an allowance for overtime (if worked).

- Fixed overheads (f) include an element for management, rent and insurance of premises associated with the process.

- βC as defined in the table on page 2 is the annual cost of the equipment associated with the process including all ducting, ventilation and any waste disposal equipment owned by the company and used for process waste.

3 Targets for improvement of the RM process

Looking at equation (1) we reduce unit cost (c) by**:**

- increasing first pass conversion (η)

- reducing utilities cost (u)

- increasing units available for sale (Q)

all of which are very obvious to the management of any process. If the market is limiting what can be sold (Q), then only u and η are important.

Where the market is not limiting then increasing Q by reducing cycle time (τ) is a clear strategy subject to not letting first pass conversion η decrease very much. Clearly scrap recovery (equation (1)) will have a vital role in offsetting any decrease in η.

3.1 Sensitivity of c to various changes

This depends on the proportions of the cost (c) represented by each factor in equation (1). These we need to establish from HRM and Techni-form. For purposes of illustration only, assume that before changes**:**

r	~	40% of c
s	~	50% of r
η	~	85%
u	~	20%
$(\ell + f + \beta C)/Q$	~	33%

which is fairly typical of polymer processing.

Then**:**

an increase in Q by 10%	decreases c by 3%
a 5% improvement in η from 85% to 89%	decreases c by 2.1%
a reduction in utilities cost (u) of 10%	decreases c by 2.35%.

All of these percentage changes are reasonable ones to aim at as it is likely that the range of values in the rotomoulding industry as a whole is at least as large as this. Given selling prices of 10-12% above cost (c), improvements of 2-3% would be significant additions to profit and competivity.

3.2 Effect of Heat Transfer Increases

The heating and cooling parts of the moulding cycle are about equal in duration (15 minutes each (Ref. 2)). Together they make up about two-thirds of the cycle time (τ), the other third being taken up by mould charging and removal of the moulding. Thus without reduction in the time for these operations, a reduction of x% in both of the heating and cooling parts of the cycle will at most reduce τ by ⅔x%.

3.2.1 Increasing effective heat transfer area on the outer surface of the mould

Results shown in Ref. 2 from the laboratory rotomoulder show a broadly steady rise in temperature of 4 ^{o}C per minute. The oven wall temperature displays a single time constant rise to 300 ^{o}C, with time constant of approximately 230 seconds, say 4 minutes.

Overall the oven rises at a mean rate of 15 ^{o}C per minute, so the heating airflow is four times as successful at heating the oven as it is in heating the mould. These results apply to the laboratory moulder, but the times and temperatures are not greatly different for the full-scale moulders at HRM and Techni-form.

The heating time constant for the mould is

$$\tau_m = \frac{hA}{\rho c_\rho} \quad (4)$$

where

h	is mean effective heat transfer coefficient for the area A(W/m^2 K)
A	is effective heat transfer (m^2)
ρ	is mould density (kg/m^3)
c_ρ	is mould specific heat (kJ/kg K)

In our experiments superficial A has been increased by introducing 10-20 mm aluminium spokes normal to the surface. Up to a point these will increase A without decreasing h in equation (4), but if placed too close together they will simply increase the boundary layer thickness (ℓ_b) and reduce h proportionately. It is reasonable to aim at a 15-25% increase in A by this means.

We need to do an experiment on the laboratory moulder to establish the quantitative change in hA and then scale it to the full-scale.

3.2.2 Increasing heat transfer coefficient

Roughly speaking

$$h \approx \rho_a c_a v_t \quad (5)$$

where

ρ_a is air density (kg/m^3)

c_a air specific heat (kJ/kg K)

v_t is turbulent velocity normal to surface A.

ρ_a, c_a are known and fixed. Turbulent velocity is typically ($0.005 \rightarrow 0.1$) times the bulk flow velocity V_b parallel with the surface A.

Flow shaping has its objective increasing V_b. Where the moulds are aluminium and thermal conductivity thus very high, there is no need for V_b to be increased everywhere, but reduction of dead spots is a good place to start.

It is reasonable to aim at a doubling of V_b in particular parts of the mould surface.

References

1 S F Bush, Scale, Order and Complexity in Polymer Processing, Proc.I.Mech.E (2000), 214 (part E), pp. 217-232.

2 O K Ademosu, D R Blackburn and G Neilson, Temperature Monitoring in Rotational Moulding, Poly. Proc. Soc. 21st Ann. Mtg. Leipzig (2005).