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Comparison of heater control strategies during unplanned stops of an automotive glass bending furnace using a lumped thermal model

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Abstract. *The paper compares three strategies for controlling the heaters of the bending zone of an automotive glass furnace during an unplanned conveyor stop: holding the set point, switching the heaters off, and lowering the set point. A lumped two-node thermal model of the zone and the glass with a PI temperature controller is developed; the deformation of the glass is characterised by a dimensionless bending index based on the Vogel-Fulcher-Tammann viscosity equation, and analytical estimates are derived for the allowable stop duration, the cooling of the zone, the recovery time and the energy saving. Calculations in Python for generalised parameters show that the glass retained in the bending zone exceeds a 10 % bending tolerance within about 2 s under all three strategies, because the zone cools at only about 1 K/min, whereas the time constant of the glass is 46 s. Switching the heaters off for 10-60 min leaves 3-15 out-of-tolerance glasses after restart, while the actual reduction in heat losses is only 0.02-0.46 kWh, i.e. 1-6 % of the energy consumed during the stop when the set point is held. The recovery time is proportional to the stop duration and is governed by the power reserve of the heaters rather than by the thermal inertia of the furnace. A rule for selecting the strategy according to the stop duration is proposed.*

Keywords: *automotive glass, gravity bending, heating furnace, unplanned stop, thermal model, PI controller, bending index, energy consumption, recovery time.*

Сравнение стратегий управления нагревателями при незапланированных остановках печи для гибки автомобильного стекла на основе сосредоточенной тепловой модели

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Аннотация. *В статье проведено сравнение трех стратегий управления нагревателями зоны гибки печи для автомобильного стекла при незапланированной остановке конвейера: поддержание заданной температуры, отключение нагревателей и снижение заданной температуры. Разработана сосредоточенная двухузловая тепловая модель зоны и стекла с ПИ-регулятором температуры. Деформация стекла характеризуется безразмерным индексом гибки, основанным на уравнении вязкости Фогеля—Фулчера—Таммана, а также получены аналитические оценки допустимой продолжительности остановки, охлаждения зоны, времени восстановления температуры и экономии энергии. Расчеты, выполненные в Python для обобщенных параметров, показывают, что стекло, находящееся в зоне гибки, превышает допустимое отклонение по индексу*

гибки на 10 % примерно через 2 с при всех трех стратегиях, поскольку зона охлаждается со скоростью всего около 1 К/мин, тогда как постоянная времени нагрева стекла составляет 46 с. При отключении нагревателей на 10–60 мин после возобновления работы образуется от 3 до 15 стекол, не соответствующих допустимым требованиям, тогда как фактическое снижение тепловых потерь составляет лишь 0,02–0,46 кВт·ч, то есть 1–6 % энергии, потребляемой во время остановки при поддержании заданной температуры. Время восстановления температуры пропорционально продолжительности остановки и определяется резервом мощности нагревателей, а не тепловой инерцией печи. Предложено правило выбора стратегии управления в зависимости от продолжительности остановки.

Ключевые слова: *автомобильное стекло, гравитационная гибка, нагревательная печь, незапланированная остановка, тепловая модель, ПИ-регулятор, индекс гибкости, энергопотребление, время восстановления.*

Avtomobil oynasini egish pechining rejadan tashqari to‘xtashlarida isitgichlarni boshqarish strategiyalarini jamlangan issiqlik modeli asosida taqqoslash

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Annotatsiya. *Maqolada avtomobil oynasini egish pechining egish zonasida konveyerning rejadan tashqari to‘xtashi vaqtida isitgichlarni boshqarishning uchta strategiyasi: belgilangan haroratni saqlab turish, isitgichlarni o‘chirish va belgilangan haroratni pasaytirish strategiyalari taqqoslangan. Egish zonasi va oyna uchun PI harorat regulyatoriga ega ikki tugunli jamlangan issiqlik modeli ishlab chiqilgan. Oynaning deformatsiyasi Fogel–Fulcher–Tammann qovushqoqlik tenglamasiga asoslangan o‘lchovsiz egilish indeksi orqali tavsiflangan. Shuningdek, ruxsat etilgan to‘xtash davomiyligi, zona haroratining pasayishi, haroratni tiklash vaqti va energiya tejamkorligi uchun analitik baholashlar olingan.*

Umumlashtirilgan parametrlar asosida Python dasturida bajarilgan hisoblashlar shuni ko‘rsatadiki, egish zonasida qolib ketgan oyna haroratni boshqarishning uchala strategiyasida ham taxminan 2 soniya ichida egilish indeksi bo‘yicha ruxsat etilgan 10 %lik og‘ish chegarasidan oshib ketadi. Buning sababi zona haroratining atigi taxminan 1 K/min tezlikda pasayishi, oyna uchun esa vaqt doimiysining 46 sekundni tashkil etishidir. Isitgichlarni 10–60 minutga o‘chirish natijasida pech qayta ishga tushirilgandan so‘ng talablarga mos kelmaydigan 3–15 ta oyna hosil bo‘ladi. Bunda issiqlik yo‘qotishlarining haqiqiy kamayishi atigi 0,02–0,46 kVt·soatni tashkil etib, belgilangan haroratni saqlab turish holatida to‘xtash davrida sarflanadigan energiyaning bor-yo‘g‘i 1–6 %iga teng bo‘ladi.

Haroratni tiklash vaqti to‘xtash davomiyligiga mutanosib bo‘lib, pechning issiqlik inersiyasiga emas, balki isitgichlarning mavjud quvvat zaxirasiga bog‘liq. To‘xtash davomiyligiga qarab boshqarish strategiyasini tanlash qoidasi taklif etilgan.

Kalit so‘zlar: *avtomobil oynasi, gravitatsion egish, isitish pechi, rejadan tashqari to‘xtash, issiqlik modeli, PI-regulyator, egilish indeksi, energiya sarfi, tiklanish vaqti.*

Introduction

Bending is one of the most demanding stages in the production of laminated

windshields. The shape of the product is formed in a continuous furnace, in which a pair of glass sheets placed on a mould is heated to the softening range and sags under its own weight. The resulting sag depth is determined by the temperature-time history of the glass, because in this range the viscosity of glass depends very strongly on temperature [1]. The control of the thermal regime of the bending zone therefore directly determines the geometry and quality of the product [2, 3].

A substantial body of work is devoted to modelling the process. G. Buonanno et al. developed a three-dimensional thermal model of the ovens used in windshield production and validated it experimentally [4]; M. Parsa et al. simulated windscreen bending using a viscoplastic formulation [5]; B. Le Corre et al. and F. Béchet et al. refined the description of radiative heat transfer in semitransparent glass in sagging and forming simulations [6, 7]; the design of a windshield heating furnace was optimised numerically in [8]. Heat transfer to float glass in heat treatment furnaces was analysed in detail by M. Rantala [9].

Control-oriented studies deal mainly with the normal operating mode. Sag bending control and on-line quality control in windshield production were considered by R. Makarov and E. Khorosheva [2, 3]. Advanced temperature controllers have been proposed for glass furnaces: a hybrid fuzzy-PI algorithm [10] and sliding mode controllers [11]. Data-driven methods are used for predicting the quality of automotive glass [12] and for optimising energy consumption in manufacturing [13]. The development of monitoring and control systems for glass furnaces is also being studied in Uzbekistan [14, 15].

Much less attention has been paid to abnormal operating modes. An unplanned stop of the conveyor, caused for example by a fault in a drive or a sensor, leaves the glass in the hot zones longer than prescribed, and a decision has to be made about the heaters: to keep the set point, to switch the heaters off, or to lower the set point. This decision is often left to the operator. For steel reheating furnaces, where the movement of the product is likewise discontinuous, model-based temperature control methods have been developed [16, 17]; for glass bending furnaces no comparable quantitative analysis is known to the authors. In particular, it remains unclear whether a reduction of the heater power during a stop can protect the glass, how much energy it actually saves, and what it costs in terms of restoring the regime after restart.

The aim of this work is to compare, on the basis of a simple thermal model, three heater control strategies for the bending zone during an unplanned stop in terms of the over-bending of the retained glass, the recovery of the regime after restart and the energy consumption, and to formulate a rule for selecting the strategy. To achieve this aim, the following tasks were addressed: a lumped model of the zone and the glass with a temperature controller was built; a dimensionless criterion of glass deformation was introduced; analytical estimates of the main indicators were derived; and the strategies

were compared numerically for stop durations from 1 to 60 min, including the sensitivity to the furnace parameters.

The scientific novelty of the work is that the strategies are compared simultaneously by three criteria using a control-oriented model, and closed-form estimates are obtained that relate the allowable stop duration, the recovery time and the energy saving to the stop duration, the time constants of the glass and the furnace, and the power reserve of the heaters.

Methodology and research

The object of study is the bending zone of a continuous electric furnace for gravity bending of windshields. Carriages with moulds move through the furnace step by step: every t_c seconds (cycle time) all carriages are shifted by one position, so that each pair of glass sheets dwells in the zone for the time t_c. The glass enters the zone at the temperature T_{in} and under normal conditions leaves it at the nominal exit temperature T_{out}. The zone temperature is measured by a thermocouple and maintained by a PI controller acting on the heater power. An unplanned stop is assumed to begin at the instant at which the next transfer should take place, so that the glass which has completed its dwell is retained in the zone for an additional time τ_s (stop duration). This is the least favourable case for that glass.

The following assumptions are made: the glass and the zone are each characterised by a single temperature (lumped model); the inner surfaces of the zone (heaters and lining) are represented by one effective temperature T_f, which is also the temperature measured by the control thermocouple; the glass exchanges heat with the zone by radiation and natural convection on both sides, and the mould and the carriage are not considered; the temperature of the incoming glass does not depend on the stop; the transfer time is neglected. Generalised parameter values are used (Table 1); they do not describe a particular furnace.

The energy balance of the glass per unit area is

$$\rho \cdot c \cdot \delta \frac{\mathrm{d}T_g}{\mathrm{d}t} = 2q, \tag{1}$$

where ρ, c, δ - density, specific heat and total thickness of the glass (pair of sheets); T_g - glass temperature; q - heat flux density to one surface of the glass; the factor 2 accounts for two-sided heating. The heat flux consists of a radiative and a convective component [18]:

$$q = \varepsilon_r \cdot \sigma \cdot \left(T_f^4 - T_g^4\right) + \alpha_c \cdot \left(T_f - T_g\right), \tag{2}$$

where ε_r - reduced emissivity of the glass-zone system; σ - Stefan-Boltzmann constant; α_c - convective heat transfer coefficient; the temperatures in the radiative term are absolute. The energy balance of the zone is

$$C_f \frac{\mathrm{d}T_f}{\mathrm{d}t} = P - 2 \cdot A_g \cdot q - K_l \cdot \left(T_f - T_a\right), \tag{3}$$

where C_f - effective heat capacity of the heaters and lining; P - heater power; A_g - area of the glass; K_l - heat loss coefficient of the zone; T_a - ambient temperature. The second term on the right-hand side is the heat absorbed by the glass, and the third term is the heat loss through the enclosure.

The applicability of the lumped description of the glass is assessed by the Biot number [18]:

$$\mathrm{Bi} = \frac{\alpha_\Sigma \cdot \delta}{2 \cdot \lambda}, \tag{4}$$

where λ - thermal conductivity of the glass; α_Σ - total heat transfer coefficient obtained by linearising (2) about the mean temperature T_m of the zone and the glass:

$$\alpha_\Sigma = \alpha_c + 4 \cdot \varepsilon_r \cdot \sigma \cdot T_m^3, \tag{5}$$

For the data of Table 1, $\alpha_\Sigma \approx 137$ W/(m²·K) and $\mathrm{Bi} \approx 0.31$, which exceeds the conventional limit of 0.1. Model (1) therefore describes the temperature of the glass averaged over its thickness. The temperature difference across the thickness, estimated as $q\delta/(4\lambda)$, is about 12 K at the beginning of the dwell and about 3 K at its end, when the bending mainly takes place. In addition, glass is semitransparent and absorbs part of the radiation within its volume, which reduces this difference [6, 7, 9]. Such accuracy is considered sufficient for comparing control strategies.

With linearised heat exchange and a constant zone temperature, (1) becomes a first-order equation with the time constant

$$\tau_g = \frac{\rho \cdot c \cdot \delta}{2 \cdot \alpha_\Sigma}, \tag{6}$$

and the temperature of a glass that entered the zone at $t = 0$ varies as

$$T_g(t) = T_f - \left(T_f - T_{in}\right) \cdot e^{-t/\tau_g}. \tag{7}$$

For the data of Table 1, $\tau_g \approx 46$ s, and (7) gives 618.3 °C at $t = t_c$, which is close to the value of 618.6 °C obtained from the nonlinear model (1)-(3). The zone itself, when the heaters are off, cools with the time constant $\tau_f = C_f/K_l \approx 9.3$ h (see below), so that $\tau_f/\tau_g \approx 725$. This separation of the time scales of the glass and the furnace by almost three orders of magnitude determines all the results that follow.

In the softening range the sag of the glass on the mould is a slow viscous flow [5], the rate of which under a given load is inversely proportional to the viscosity η. The temperature dependence of the viscosity is described by the Vogel-Fulcher-Tammann (VFT) equation [1]:

$$\lg \eta = A + \frac{B}{T_g - T_0}, \tag{8}$$

where A, B, T_0 - empirical coefficients. They were determined from three reference points of clear float glass given in [19]: the strain point 511 °C ($\lg \eta$ = 13.5), the annealing point 548 °C ($\lg \eta$ = 12.0) and the softening point 715 °C ($\lg \eta$ = 6.6), with η in Pa·s. The coefficients obtained in this way (Table 1) serve only for interpolation within 511-715 °C and should not be used outside this interval. To characterise the deformation accumulated by a glass irrespective of the geometry of the product, a dimensionless bending index is introduced:

$$I_b = \frac{\int_0^{t_d} \frac{\mathrm{d}t}{\eta \cdot \left(T_g(t)\right)}}{\int_0^{t_c} \frac{\mathrm{d}t}{\eta \cdot \left(T_g^n(t)\right)}}, \tag{9}$$

where t_d - actual dwell time of the glass in the zone; T_g^n - glass temperature in the nominal cycle. For a glass processed in the nominal regime $I_b = 1$; $I_b > 1$ means over-bending and $I_b < 1$ under-bending. A glass is regarded as being within tolerance if $|I_b - 1| \le \varepsilon_b$. Index (9) assumes linear viscous flow and ignores the limiting action of the mould; large values of the index therefore have no geometric meaning and indicate only that the glass is certainly lost.

For the retained glass, the temperature of which at the beginning of the stop equals T_{out} and does not decrease quickly, (9) leads to the estimate

$$I_b(\tau_s) \approx 1 + \frac{\tau_s}{t_{eq}}, \qquad t_{eq} = \eta(T_{out}) \int_0^{t_c} \frac{\mathrm{d}t}{\eta \cdot \left(T_g^n(t)\right)}, \tag{10}$$

where t_{eq} - equivalent bending time, i.e. the time for which the glass would have to be held at its exit temperature to accumulate the nominal deflection. Hence the allowable stop duration for the glass in the bending zone is $\tau_{adm} \approx \varepsilon_b t_{eq}$. Since the glass continues to heat up after the stop, (10) is a lower estimate of the index and an upper estimate of the allowable duration.

Controller and control strategies

The zone temperature is controlled by a PI controller with a limited output [20]:

$$P = \mathrm{sat}\left\{K_p \left[e + \frac{1}{T_i}\int_0^t e\ \mathrm{d}t\right]\right\}, \qquad e = T_{sp} - T_f, \tag{11}$$

where K_p, T_i - gain and integral time of the controller; T_{sp} - set point; sat denotes the limitation of the output to the range from 0 to P_{max}. The integration is suspended while the output is limited (anti-windup) [20]. Three strategies are considered for the interval of the stop:

strategy A - the set point is kept at its nominal value T_{sp};

strategy B - the heaters are switched off ($P = 0$) and the integral term of the

controller is frozen;

strategy C - the set point is lowered by ΔT_{sb} to the value $T_{sp} - \Delta T_{sb}$.

In all cases the nominal set point and normal control are restored at the instant of restart.

While the heaters are off and the retained glass has already approached the zone temperature, the second term on the right-hand side of (3) is small, and the zone cools according to

$$T_f(t) = T_a + \left(T_{f0} - T_a\right) \cdot e^{-t/\tau_f}, \qquad \tau_f = \frac{C_f}{K_l}, \tag{12}$$

where T_{f0} - zone temperature at the beginning of the stop; the time t is counted from the beginning of the stop. The temperature deficit of the zone at the instant of restart is

$$\Delta T_f = \left(T_{f0} - T_a\right)\left(1 - e^{-\tau_s/\tau_f}\right) \approx \frac{P_l \tau_s}{C_f}, \tag{13}$$

where $P_l = K_l\left(T_{f0} - T_a\right)$ - power of the heat losses in the nominal regime. After restart the controller output is limited, and the deficit is eliminated by the power reserve $P_{max} - P_n$, where P_n is the mean heater power in the nominal cycle. The recovery time is therefore

$$t_{rec} \approx \frac{C_f \cdot \Delta T_f}{P_{max} - P_n} \approx \frac{P_l}{P_{max} - P_n}\tau_s. \tag{14}$$

Thus, for stops that are short compared with τ_f, the recovery time is proportional to the stop duration and does not depend on the heat capacity of the furnace: a heavier furnace cools more slowly, but it is reheated just as slowly. The coefficient of proportionality is the ratio of the loss power to the power reserve of the heaters.
As regards energy, while the heaters are off the furnace gives up stored heat, which has to be returned after restart. The only real saving is the reduction in heat losses caused by the lower zone temperature. Integrating the difference of the losses over the stop with the use of (12) gives

$$\Delta E_l = P_l \cdot \left[\tau_s - \tau_f \cdot \left(1 - e^{-\tau_s/\tau_f}\right)\right] \approx \frac{P_l \cdot \tau_s^2}{2 \cdot \tau_f}. \tag{15}$$

Relative to the energy $P_l\tau_s$ consumed during the stop under strategy A, the saving is approximately $\tau_s/\left(2\tau_f\right)$, i.e. it is negligible for stops that are short compared with τ_f. For strategy C the estimates (13)-(15) hold until the zone temperature reaches the lowered set point; after that the deficit remains equal to ΔT_{sb}. The depth of the set-point reduction compatible with an admissible recovery time t_{adm} follows from (14):

$$\Delta T_{sb} \le \frac{(P_{max} - P_n) \cdot t_{adm}}{C_f}. \tag{16}$$

The strategies were compared by the following criteria: the maximum temperature of the retained glass and its bending index; the number N of glasses after restart whose index is outside the tolerance (the recovery time is then Nt_c); and the energy consumed by the heaters from the beginning of the stop until 40 min after restart, together with its components - the heat losses and the heat absorbed by the glass.

The parameters are given in Table 1. The density and thermal conductivity of the glass were taken from [19]. The specific heat was adopted with allowance for its increase with temperature in comparison with the room-temperature value of 0.88 kJ/(kg·K) [19], and the reduced emissivity was taken somewhat lower than the hemispherical emissivity of 0.84 [19] because glass is partly transparent to short-wave radiation [9]. The parameters of the zone and the controller settings are generalised values. Equations (1)-(3) and (11) were integrated by the explicit Euler method with a step of 0.05 s in Python using the NumPy library; the stop was introduced after 40 nominal cycles, when the periodic regime had been established. The stop duration was varied from 1 to 60 min, and the heat capacity of the zone and the maximum heater power were varied to assess the sensitivity of the results.

Table 1. Calculation parameters

Parameter	Symbol	Value
Total thickness of the glass (two sheets of 2.1 mm)	δ	4.2 mm
Density of the glass	ρ	2500 kg/m³
Specific heat of the glass	c	1200 J/(kg·K)
Thermal conductivity of the glass	λ	0.937 W/(m·K)
Reduced emissivity	ε_r	0.80
Convective heat transfer coefficient	α_c	10 W/(m²·K)
Area of the glass	A_g	1.4 m²
Temperature of the incoming glass	T_{in}	560 °C
Set point of the zone temperature	T_{sp}	640 °C
Cycle time	t_c	60 s
Effective heat capacity of the zone	C_f	400 kJ/K (200-800)
Heat loss coefficient	K_l	12 W/K
Ambient temperature	T_a	25 °C
Maximum heater power	P_{max}	45 kW (35-60)
Controller gain and integral time	K_p, T_i	10 kW/K; 120 s
VFT coefficients (511-715 °C; temperature in °C)	A, B, T_0	-20.59; 27 407 °C; -292.9 °C
Tolerance of the bending index	ε_b	0.10
Set-point reduction in strategy C	ΔT_{sb}	10 K
Stop duration	τ_s	1-60 min

Results

In the nominal periodic regime the controller keeps the zone temperature within 639.9-640.2 °C; the glass leaves the zone at T_{out} = 618.6 °C, and the mean heater power is P_n = 24.6 kW, of which P_l = 7.4 kW covers the heat losses and the remainder is absorbed by the glass. During the dwell lg η of the glass decreases from 11.5 to 9.5, and near the exit temperature the viscosity halves for every 9 K of temperature rise. As a result, 73 % of the nominal deflection is accumulated during the last 20 s of the 60-s dwell, and the equivalent bending time defined in (10) is only t_{eq} = 18.4 s. Figure 1 shows the transients for a stop of 20 min.

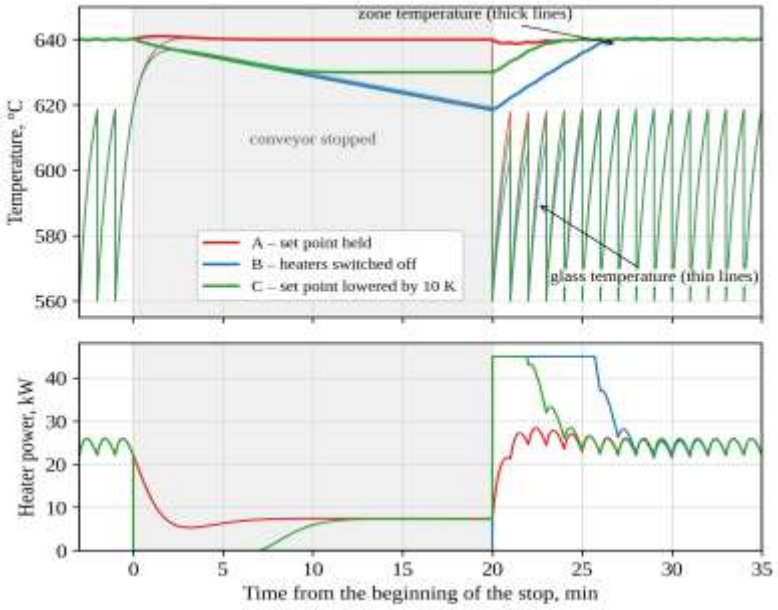

Figure 1. Zone temperature, glass temperature and heater power during a 20-min stop and the subsequent recovery

Under strategy A the zone temperature remains at the set point, and the retained glass approaches the zone temperature within 2-3 min. Under strategy B the zone cools almost linearly at a rate of 1.1 K/min, which agrees with (13), and reaches 618.5 °C by the end of the stop. Under strategy C the transient coincides with that of strategy B during the first 6-7 min, after which the zone settles at the lowered set point of 630 °C. After restart the heaters operate at full power for 5.7 min under strategy B and for 1.9 min under strategy C.

Figure 2 shows the bending index of the retained glass as a function of the stop duration. Under all three strategies the index exceeds the tolerance limit of 1.1 after 1.75 s (the estimate (10) gives 1.84 s). The curves diverge only after 2-3 min, when the index already exceeds 20, i.e. when the glass is certainly lost.

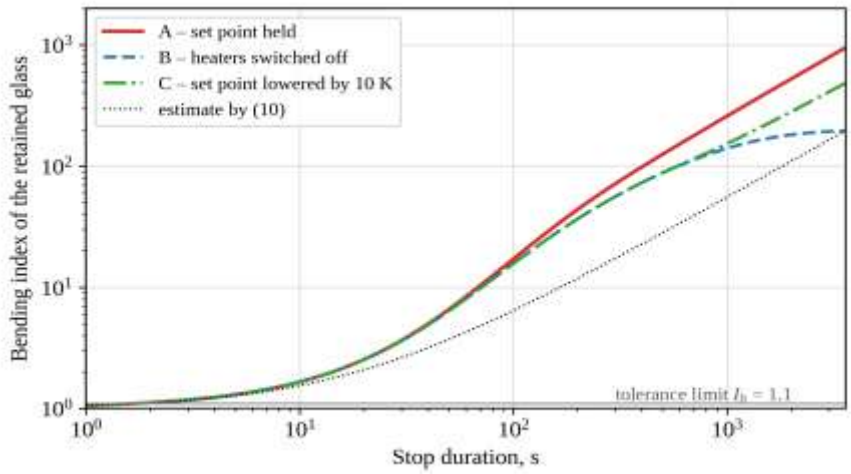

Figure 2. Bending index of the retained glass versus stop duration

Table 2 gives, for five stop durations, the indicators that are not shown in the figures: $T_{g.max}$ - maximum temperature of the retained glass; T_{fr} - zone temperature at the instant of restart; E_s - energy consumed by the heaters during the stop.

Table 2. Comparison of the strategies

τ_s, min	Strategy	$T_{g.max}$, °C	T_{fr}, °C	E_s, kWh
2	A	639.6	641.0	0.43
	B	636.8	637.2	0.00
	C	636.8	637.2	0.00
5	A	640.6	640.2	0.72
	B	636.9	634.0	0.00
	C	636.9	634.0	0.00
10	A	640.6	640.0	1.31
	B	636.9	628.8	0.00
	C	636.9	630.1	0.15
30	A	640.6	640.0	3.77
	B	636.9	608.3	0.00
	C	636.9	630.0	2.56
60	A	640.6	640.0	7.46
	B	636.9	578.9	0.00
	C	636.9	630.0	6.19

The recovery of the regime after restart is illustrated in Figure 3. Under strategy A all glasses after restart remain within the tolerance: the PI controller compensates the step change of the load, and the lowest value of the index is 0.94. Under strategy B the number of out-of-tolerance glasses grows almost in proportion to the stop duration: 1 at 5 min, 3 at 10 min, 8 at 30 min and 15 at 60 min. The estimate by (13) and (14) gives 1.8, 3.6, 10.6 and 20.6 cycles, respectively. It is an upper estimate, because a cooler zone transfers less heat to the glass, which increases the actual power reserve, and because the count stops as soon as the index enters the tolerance band. Under

strategy C the number is limited to 3 for any stop longer than about 10 min, in agreement with (14), which gives 3.3 cycles for $\Delta T_f = \Delta T_{sb}$ = 10 K.

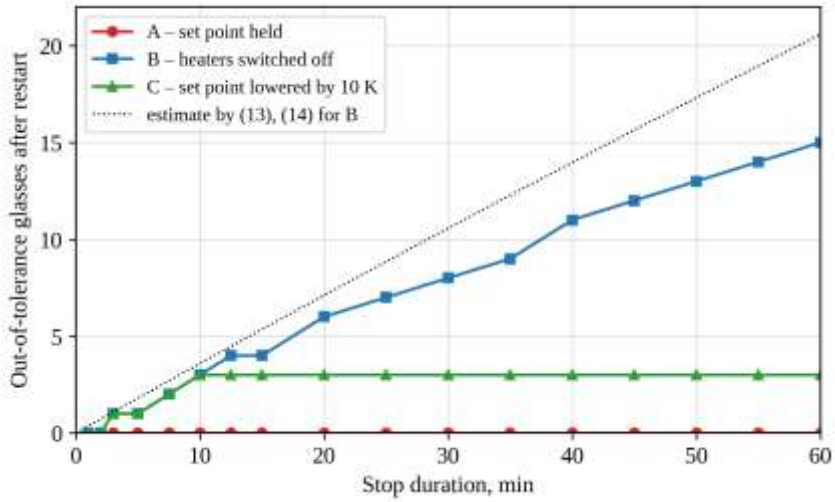

Figure 3. Number of out-of-tolerance glasses after restart versus stop duration

The energy indicators are compared in Figure 4. Under strategy A the heaters consume 1.31, 3.77 and 7.46 kWh during stops of 10, 30 and 60 min. Under strategy B nothing is consumed during the stop itself, but the total consumption over the stop and the recovery period is lower by only 0.12, 0.76 and 2.31 kWh, respectively. Moreover, only 0.016, 0.124 and 0.461 kWh of this is a reduction in heat losses, i.e. 1.2, 3.3 and 6.2 % of the energy consumed during the stop under strategy A. The rest is heat that was not delivered to the under-heated glasses after restart; it corresponds to rejected product rather than to a saving. The estimate (15) gives 0.011, 0.098 and 0.385 kWh for the interval of the stop alone; the difference from the model is the additional reduction in losses during the recovery.

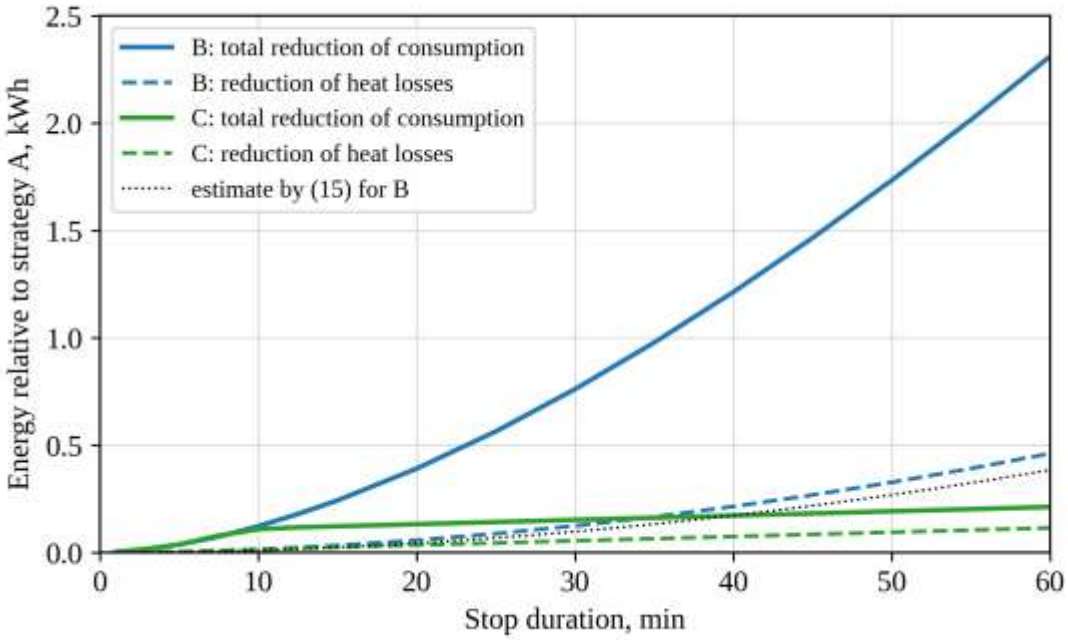

Figure 4. Reduction of energy consumption relative to strategy A versus stop duration

Table 3 shows the sensitivity of the results to the parameters of the furnace for strategy B and a stop of 10 min. Halving or doubling the heat capacity of the zone changes the zone temperature at restart (618.6-634.3 °C) but hardly changes the number of out-of-tolerance glasses (2-3), as predicted by (14), whereas the reduction in heat losses varies in inverse proportion to the heat capacity, as predicted by (15). By contrast, the power reserve has a strong effect: with a maximum heater power of 35, 45 and 60 kW the number of out-of-tolerance glasses is 5, 3 and 2.

Table 3. Sensitivity to the furnace parameters (strategy B, stop of 10 min)

Varied parameter	T_{fr}, °C (model)	T_{fr}, °C by (12)	N (model)	t_{rec}/t_c by (14)	ΔE_l, kWh (model)	ΔE_l, kWh by (15)
C_f = 200 kJ/K	618.6	618.3	3	3.6	0.029	0.022
C_f = 400 kJ/K (base)	628.8	629.0	3	3.6	0.016	0.011
C_f = 800 kJ/K	634.3	634.5	2	3.6	0.008	0.006
P_{max} = 35 kW	628.8	629.0	5	7.0	0.019	0.011
P_{max} = 60 kW	628.8	629.0	2	2.1	0.014	0.011

The first conclusion that follows from the results is that the glass located in the bending zone at the moment of an unplanned stop cannot be protected by controlling the heaters. The reason is the separation of time scales: the glass follows the zone temperature with a time constant of 46 s and accumulates the nominal deflection in an equivalent time of 18 s, whereas the zone, even with the heaters switched off, cools at about 1 K/min. The allowable stop duration is therefore about 2 s irrespective of the strategy. This is consistent with the strong temperature dependence of the viscosity of

glass [1] and with the decisive role of the temperature-time regime in sag bending [2]. For the control system this means that a glass caught in the bending zone by a stop lasting more than a few seconds should be marked as rejected, and that protecting it would require means that act within seconds, which lies outside heater control.

The second conclusion concerns energy. Switching the heaters off during a stop looks like an obvious saving, since the consumption during the stop falls to zero. The balance over the stop and the recovery shows, however, that the furnace merely spends its stored heat and takes it back after restart. According to (15), the real saving relative to holding the set point is about $\tau_s/(2\tau_f)$; for the furnace considered it is 1 % for a stop of 10 min and 5-6 % for a stop of one hour. The larger apparent reduction in consumption obtained in the model is the heat that the under-heated glasses did not receive.

The third conclusion is that the price of lowering the zone temperature is a recovery period that is proportional to the stop duration. According to (14), the proportionality coefficient is the ratio $P_l/(P_{max} - P_n)$, equal to 0.36 for the base data: every 10 min with the heaters off costs about three out-of-tolerance glasses after restart. This coefficient does not depend on the thermal inertia of the furnace and can be reduced only by increasing the power reserve of the heaters, as the results in Table 3 confirm.

In steel reheating furnaces the heated product is massive and its temperature changes slowly, so that the furnace temperature set points can be adapted to the movement of the product by model-based control [16, 17]. In glass bending the situation is the opposite: the thin glass responds within tens of seconds, much faster than the zone, and set-point actions cannot follow it. For this reason the tasks of control during a stop shift from protecting the retained glass to tracking and rejecting it and to organising the restart.

The following rule for selecting the strategy follows from the results:

If the stop lasts longer than $\tau_{adm} \approx \varepsilon_b t_{eq}$ (about 2 s for the data considered), the glass in the bending zone is marked as rejected in the tracking system; this does not depend on the strategy.

For stops shorter than about $0.1\tau_f$ (about one hour for the furnace considered) the set point should be held (strategy A): the possible reduction in heat losses does not exceed about 5 % of the consumption during the stop, whereas any decrease in the zone temperature produces out-of-tolerance glasses after restart.

For longer stops the set point should be lowered (strategy C) by a depth limited according to (16) by the admissible recovery time, and the nominal set point should be restored before restart; the restart of the conveyor should be interlocked until the zone temperature has returned to the tolerance band. Without the glass load the required pre-

heating time is approximately $C_f \Delta T_{sb}/(P_{max} - P_l)$, which is 1.8 min for a reduction of 10 K.

Switching the heaters off completely (strategy B) is justified only for stops comparable with τ_f, i.e. essentially when the furnace is being shut down.

From the standpoint of automation, the rule uses only algebraic expressions and a timer and can be implemented in a programmable logic controller (PLC) as a simple state machine. Its parameters can be identified from the data archived by the SCADA system: the time constant τ_f from a cooling curve recorded with the heaters off, and the powers P_n and P_l from the recorded heater power in the nominal regime and during a stop with the set point held.

The work has the following limitations. Only one zone is considered, and the temperature of the incoming glass is assumed constant, although during a stop the glass in the upstream zones is also soaked and enters the bending zone hotter after restart. The heaters and the lining are described by one effective temperature, whereas in a real furnace the heaters respond faster than the lining; the thermal mass of the moulds is neglected. The glass is treated as a lumped body, the deformation criterion is simplified, and the parameters are generalised rather than identified for a particular furnace, so the numerical values should be regarded as estimates. At the next stage it is planned to identify the model from the archived data of an industrial furnace and to extend it to several zones.

Conclusion

A lumped thermal model of the bending zone with a PI controller and a dimensionless bending index has been used to compare three heater control strategies during an unplanned conveyor stop. For the generalised data considered, the glass retained in the bending zone leaves the 10 % bending tolerance after about 2 s under any strategy, because the time constant of the glass (46 s) is almost three orders of magnitude smaller than that of the furnace (9.3 h). Switching the heaters off for 10-60 min produces 3-15 out-of-tolerance glasses after restart, while the real reduction in heat losses amounts to only 1-6 % of the energy consumed during the stop when the set point is held. The derived estimates show that the recovery time is proportional to the stop duration with a coefficient equal to the ratio of the loss power to the power reserve of the heaters, and that the relative energy saving is about half the ratio of the stop duration to the time constant of the furnace. It is therefore recommended to hold the set point during short stops, to use a limited set-point reduction with an interlocked restart during long stops, and to treat the glass in the bending zone as rejected. The proposed estimates and selection rule can be implemented in PLC- and SCADA-based control systems of bending furnaces.

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