Energy consumption and capacity utilization of galvanizing furnaces

S G Blakey* and **S B M Beck**
Department of Mechanical Engineering, University of Sheffield, Sheffield, UK

Abstract: An explicit equation leading to a method for improving furnace efficiency is presented. This equation is dimensionless and can be applied to furnaces of any size and fuel type for the purposes of comparison. The implications for current furnace design are discussed. Currently the technique most commonly used to reduce energy consumption in galvanizing furnaces is to increase burner turndown. This is shown by the analysis presented here actually to worsen the thermal efficiency of the furnace, particularly at low levels of capacity utilization. Galvanizing furnaces are different to many furnaces used within industry, as a quantity of material (in this case zinc) is kept molten within the furnace at all times, even outside production periods. The dimensionless analysis can, however, be applied to furnaces with the same operational function as a galvanizing furnace, such as some furnaces utilized within the glass industry.

Keywords: furnace, energy efficiency, combustion, dimensional analysis, capacity utilization

NOTATION

A	area (m^2)
L	length (m)
m_d	turndown of furnace at demand
$\dot{m}$	absolute production rate (t/h) $= M/t_{\text{total}}$
$\dot{m}_{\max}$	maximum production rate (t/h)
$\dot{m}_{\text{prod}}$	relative production rate (t/h) $= M/t_{\text{prod}}$
M	total production (t)
$\dot{q}$	Heat flux (kW/m^2)
$\dot{q}_{\text{avg, max}}$	average heat flux at the maximum firing rate (kW/m^2)
$\hat{q}_w$	heat required to galvanize the work (kW h/t)
$\dot{Q}$	heat transfer rate (kW)
r_{rad}	ratio of radiative heat flux to convective heat flux
SEC	specific energy consumption (kW h/t)
t	time (h)
U_c	utilization of covers
U_{cap}	capacity utilization
η	efficiency
η_{th}	thermal efficiency
τ	proportion of time spent under a particular condition

Subscripts

avg	average value
c	property relating to the covers used over the surface of the molten zinc
crit	critical value
d	demand
f	value relating to the flue/flue gases
flame	value relating to the flame
HF	value relating to the high-fire condition
HX	value relating to heat exchange
kettle	value relating to the kettle
LF	value relating to the low-fire condition
prod	value relating to production
s	property relating to the surface of the molten zinc
total	value relating to the total period under analysis
uncovered	value relating to periods while covers are not in use
zinc	value relating to the zinc contained in the kettle

1 INTRODUCTION

Approximately half of the zinc produced worldwide is used as a coating in the galvanizing of steel (and iron) for the purposes of corrosion protection. The majority of galvanized items are coated using the hot-dip method of galvanizing, where work is dipped into a kettle containing molten

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**Corresponding author: Department of Mechanical Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, UK.*

zinc which is kept molten using a galvanizing furnace. The hot dip galvanizing industry in the United Kingdom galvanized 802 000 t of steel product in 2002 [**1**]. It has been suggested that the galvanizing industry uses around 18 per cent of the energy that would be used in the replacement of corroded structures [**2**].

In order to contain the zinc, a bath or kettle is used in which the zinc is kept in a molten state at 450 °C. The process requires a relatively large surface area of zinc to permit the dipping of product into the kettle. The zinc is typically heated through the kettle wall, which can be classified as indirect heating and is shown in Fig. 1.

Furnaces that heat the zinc indirectly have a combustion gallery between the kettle and the exterior of the furnace to facilitate the transfer of heat from the combustion gases to the zinc. Three main types of indirect gas fired furnace are in use within the industry: flat-flame, forced-circulation and high-velocity furnaces [**3**]. Furnaces that supply heat directly to the zinc (not through the kettle wall), such as immersion burners, are in use but are prone to cracking of the ceramic shell surrounding the immersed burner [**4**].

Indirectly heated furnaces combine both the hydrodynamic and heat transfer requirements of the furnace in the kettle wall, restricting the types of material suitable to materials such as low-carbon, low-silicon steel. However, the molten zinc causes erosion of a steel kettle wall by creating a zinc–iron alloy, some of which adheres to the kettle wall, limiting further erosion. This erosion results in a limited kettle life span, typically between 5 and 8 years, after which it must be replaced [**5**].

The high-velocity furnace is one of the leading designs of indirectly fired galvanizing furnace in the world today. It offers a far more uniform heat flux than the flat-flame furnaces and can be operated with a smaller number of gas burners [**3**]. The furnaces traditionally have two settings, high and low fire, and are controlled by proportional logic circuitry and a thermocouple monitoring the zinc temperature. The turndown of the furnace, m_d, is defined as the ratio of heat input on high fire to the heat input on low fire.

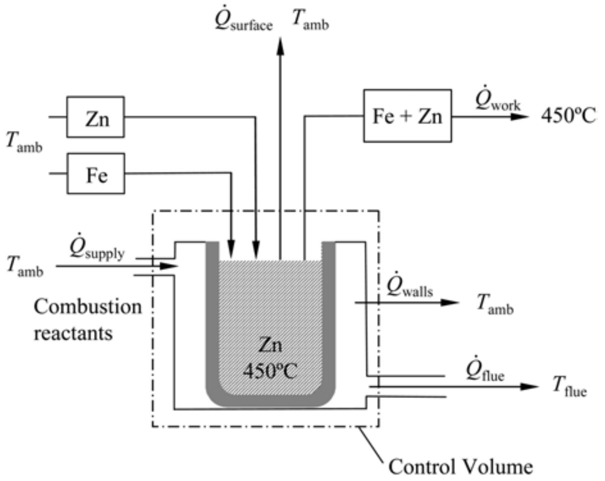

Fig. 1 Schematic showing energy and mass flows in and out of a simplified indirectly fired galvanizing furnace

In analysing the energy consumption of many types of production plant, it is common to quantify the energy usage using a specific energy consumption (SEC) term. This is most commonly defined as the energy consumed per unit of product produced and is usually constant at all levels of production. By convention, its units are kJ/kg, although kW h/t is a more meaningful unit as the industry production is measured in t and is invoiced for its energy consumption in kW h throughout Europe.

In industries such as galvanizing, energy is consumed even during idling periods, when no product is being produced by the plant. This is because large quantities of material, in this case, zinc, must be maintained in a molten state. Hence, the SEC is not constant and is dependent on the production rate of the plant [**6**]. This dependence can be seen for a typical furnace in Fig. 2 and was assumed by Haarmann to be parabolic [**7**]. The use of SEC alone as a measure of energy consumption for comparison purposes is not valid, as a finite production rate is required fully to describe the energy use. Such an analysis is therefore only useful when production is a key driver of the energy usage at the site [**8**].

This problem prompted the glass industry (which, under certain conditions, can be considered analogous to the galvanizing industry) to develop alternative methods for comparing energy consumption [**9**]. However, the formulae developed were only applicable to the energy consumption under idling conditions, and could not be applied for the comparison of furnaces during production [**10**].

A new method for analysis and comparing the energy consumption of galvanizing furnaces is presented that can be applied at any rate of production, for furnaces of any size, shift pattern or fuel type. This method can also be used for furnaces in other industries provided they have a similar idling energy consumption.

2 GALVANIZING ENERGY CONSUMPTION

This description of the galvanizing furnace energy consumption is initially restricted to indirectly heated furnaces where the heat input (supply) is by the combustion of natural gas. In such furnaces where heat is supplied by fossil fuel combustion, only a certain proportion of the energy supplied is transferred to the zinc, the remainder being the energy associated with the furnace exhaust, $\dot{Q}_f$.

Simple first law energy analysis such as that indicated by the energy flows shown in Fig. 1 leads quickly to the establishment of an implicit energy balance for galvanizing furnaces [**11**] which has been explicitly stated by Wubbenhorst [**12**] as

$$\dot{Q}_{supply} = \dot{Q}_w + \dot{Q}_s + \dot{Q}_{walls} + \dot{Q}_f \tag{1}$$

The sum of $\dot{Q}_w$ (the heat required to galvanize and melt out replacement zinc) and $\dot{Q}_s$ (the heat lost from the exposed

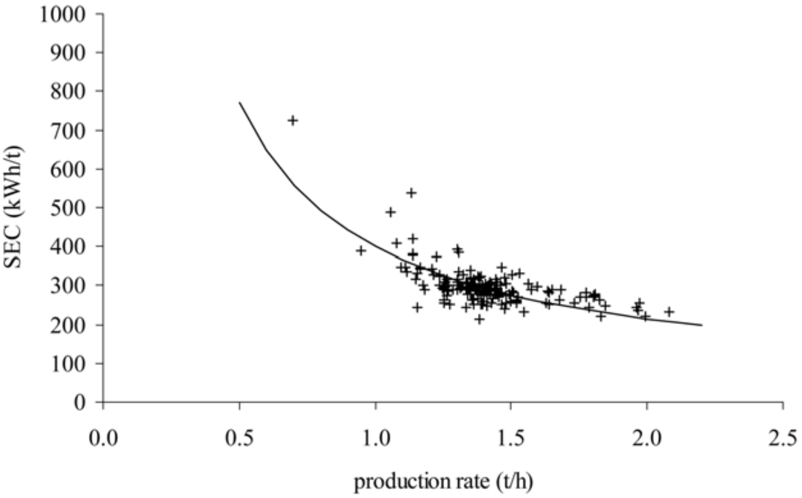

Fig. 2 Dependence of SEC on production rate for galvanizing furnaces (data taken weekly from a furnace maintaining 125 t of molten zinc) [**19**]

surface of molten zinc) in equation (1) can be described as the demand of the furnace. Regardless of what method is used for heating, sufficient heat needs to be supplied to the zinc to replace the energy lost both from the surface and as a result of the galvanizing process itself. These terms can be considered independent of furnace design and are merely functions of the production rate and the exposed surface area of molten zinc. By incorporating these heating demands into $\dot{Q}_{\mathrm{demand}}$ (the furnace demand), equation (1) can further be reduced to equation (2). The authors have already shown that the energy lost through the exterior walls of the furnace, $\dot{Q}_{\mathrm{walls}}$, can be assumed to be negligible, and is roughly 2 per cent of the total consumption [**13**]

$$\dot{Q}_{\mathrm{supply}} = \dot{Q}_{\mathrm{demand}} + \dot{Q}_{\mathrm{f}} \tag{2}$$

When expressing the overall efficiency of the galvanizing furnace, the first and second laws of thermodynamics need to be upheld, otherwise the results will be misleading [**14**]. Efficiency can be defined as the ratio of desired output to required input, or, in the context of the galvanizing plant, the overall thermal efficiency of the furnace can be described as [**12**]

$$\eta_{\mathrm{th}} = \frac{\dot{Q}_{\mathrm{demand}}}{\dot{Q}_{\mathrm{supply}}} = \frac{\dot{Q}_{\mathrm{supply}} - \dot{Q}_{\mathrm{f}}}{\dot{Q}_{\mathrm{supply}}} \tag{3}$$

Equation (3) has the additional benefit of being one of the easiest definitions of efficiency to be quantified in a real plant, assuming the furnace has orifice plates on the gas and air lines from which the flowrate can be calculated, and there is a thermocouple in the flue.

This single equation emphasizes the importance of the flue gas temperature to the thermal efficiency of the furnace. As commented by Thring [**10**], ‘the higher the flue temperature above the working temperature of the furnace, the more inefficient the furnace will be’. In addition, flue temperatures below the product temperature (450 °C in the case of zinc for galvanizing purposes) will actually result in the cooling of the kettle by the combustion gases and result in lower efficiencies. The existence of flue temperatures below the furnace operating temperature might seem counterintuitive; however, this may be the situation if the levels of excess air required for stable combustion are very high. It would therefore seem sensible to design the high and low fires of the furnace (high fire having the higher flue temperature) so that a minimum of time is spent on high fire, and, under idling conditions, the zinc temperature is maintained by using low fire alone. A more detailed review of the variables in equation (1) and typical values for the constants have been given by the present authors in previous work [**13**].

The heat transferred to the kettle from the furnace $\dot{Q}_{\mathrm{demand}}$, and hence the flowrate of work, $\dot{m}$, through the galvanizing furnace are limited by one of two factors. The first and more easily understood is the maximum heat output of the burner system. The second, more critical, factor is that the ultimate heat demand may be limited by the maximum acceptable heat flux through the kettle wall. As described above, the alloying reaction between the molten zinc and the kettle wall causes the kettle wall to be eroded over time. This rate of wear is exponentially dependent on the heat flux through the wall [**15**, **16**] and becomes unacceptably high above $\dot{q}_{\mathrm{crit}} = 29\ \mathrm{kW/m^2}$ [**17**].

These limitations lead to the definition of a maximum production rate, $\dot{m}_{\mathrm{max}}$ [**18**], which can be achieved for a particular furnace. This is either at the maximum heat supply of the furnace or at the point at which the critical heat load is reached. If the furnace is designed such that at $\dot{m}_{\mathrm{max}}$ the furnace is running 100 per cent of the time at its high-fire setting, the critical wear rate will always be the governing condition.

This is supported by the established industrial practice within the industry that deeper kettles with a smaller surface area are more energy efficient. The kettle wall for heat transfer will be larger, lowering the wear rate, and the surface area of exposed zinc will be lower, reducing $\dot{Q}_{\text{demand}}$.

Work has been carried out by Meunier to develop a general expression for the SEC of a galvanizing furnace [**19**], showing that

$$\text{SEC}_{\text{supply}} = \frac{\hat{q}_{\text{w}}}{\eta_{\text{prod}}} + \frac{A_{\text{s}}\dot{q}_{\text{s}}}{\eta_{\text{prod}}\dot{m}}\left(\frac{t_{\text{uncovered}}}{t_{\text{prod}}}\right) + \frac{\dot{Q}_{\text{losses}}}{\eta\dot{m}} \tag{4}$$

where η_{prod} is the efficiency of the furnace during production periods and η_{idling}, is the efficiency while idling. The $\dot{Q}_{\text{losses}}$ term combines heat losses during production and heat losses during idling periods. This was then defined as

$$\dot{Q}_{\text{losses}} = \eta\left[\frac{1}{\eta_{\text{idling}}} + \frac{t_{\text{prod}}}{t_{\text{total}}}\left(\frac{1}{\eta_{\text{idling}}} + \frac{1}{\eta_{\text{prod}}}\right)\right] \tag{5}$$

Meunier's work recognizes the production dependent nature of SEC shown in Fig. 2, and that, at low levels of production, the losses from the surface and walls of the tank become more influential. Equation (4) also identifies that the time spent without insulative covers over the exposed area of molten zinc may well be longer than the time spent in production.

Equations (4) and (5) assume that there are only two levels of efficiency, one for idling and one for production. However, the $\text{SEC}_{\text{supply}}$ and $\text{SEC}_{\text{demand}}$ will both vary as the production rate increases, and, as more time is spent on high fire, the average efficiency will decrease.

It can be seen that, as $\dot{m}$ tends to $\dot{m}_{\max}$, the SEC decreases. This improvement in the operation of the furnace with respect to $\dot{m}_{\max}$ is known within the industry as capacity utilization, which was first introduced as a qualitative measure in 1956 [**6**]. Work carried out by the authors has led to the quantitative expression of capacity utilization [**13**] as

$$U_{\text{cap}} = \frac{\dot{m}}{\dot{m}_{\max}} \tag{6}$$

Thus, when U_{cap} is unity, the furnace will be operating at its maximum throughput, demand and supply of energy. This term removes the effect of a particular furnace design on the SEC values, and classifies furnaces into design groups [**13**].

Further work by the authors on the basis of the statistical analysis of energy consumption for a range of galvanizing furnaces has shown that the curve of SEC versus $\dot{m}$ (for one furnace) and U_{cap} (for a range of furnaces) takes the shape of a hyperbola and can be described by equation (7) [**20**], rather than the parabolic shape proposed by Haarmann [**7**]

$$\text{SEC} = a + \frac{b}{U_{\text{cap}}} \tag{7}$$

where a and b are constants and can be found from the performance of a particular furnace, or a group of furnaces of the same design. These constants are independent of production rate and shift pattern, and can be used for the objective comparison of furnaces of different sizes and designs.

3 THEORETICAL ANALYSIS. PART 1: DEMAND FOR HEAT

Instead of trying to produce an expression for the $\text{SEC}_{\text{supply}}$ directly, as seen in references [**9**] and [**19**], an expression for the $\text{SEC}_{\text{demand}}$ has been developed, remembering that $\dot{Q}_{\text{demand}}$ is independent of the furnace design. Heat transfer $\dot{Q}_{\text{demand}}$ can be defined as the sum of the three following contributions:

1. The energy required to heat the item to be galvanized to 450 °C and to melt out replacement zinc for that which is removed from the bath ($\hat{q}_{\text{w}} = 66$ kW h/t) [**13**]:

$$\dot{Q}_{\text{work}} = \dot{m}\hat{q}_{\text{w}} \tag{8}$$

2. The energy required to maintain the zinc temperature during operation by replacing the energy lost from the surface of the zinc ($12 < \dot{q}_{\text{s}} < 17$ kW/m^2) [**4**, **11**, **21**]:

$$= \left(\frac{t_{\text{total}} - t_{\text{c}}}{t_{\text{total}}}\right)A_{\text{s}}\dot{q}_{\text{s}} \tag{9}$$

3. The energy required to maintain the zinc temperature when not in production, where the exposed surface of the zinc is covered by a thermal protective layer which limits the loss from the surface, $\dot{q}_{\text{c}}$.

$$= \left(\frac{t_{\text{c}}}{t_{\text{total}}}\right)A_{\text{s}}\dot{q}_{\text{c}} \tag{10}$$

This can be written algebraically as equation (11)

$$\dot{Q}_{\text{demand}} = \dot{m}\hat{q}_{\text{w}} + A_{\text{s}}\dot{q}_{\text{s}} - A_{\text{s}}\left(\frac{t_{\text{c}}}{t_{\text{total}}}\right)(\dot{q}_{\text{s}} - \dot{q}_{\text{c}}) \tag{11}$$

where the ratio $t_{\text{c}}/t_{\text{total}}$ is a dimensionless factor similar to that shown in equation (4), indicating the proportion of time that covers are used. If the plant is in continuous operation, or covers are not used, equation (11) would reduce to

$$\dot{Q}_{\text{demand}} = \dot{m}\hat{q}_{\text{w}} + A_{\text{s}}\dot{q}_{\text{s}} \tag{12}$$

By dividing through equation (11) by $\dot{m}$, an equation of the specific energy consumption demand ($\text{SEC}_{\text{demand}}$) can be defined as

$$\text{SEC}_{\text{demand}} = \hat{q}_{\text{w}} + \frac{A_{\text{s}}\dot{q}_{\text{s}} - (t_{\text{c}}/t_{\text{total}})(\dot{q}_{\text{s}} - \dot{q}_{\text{c}})}{\dot{m}} \tag{13}$$

This is similar in form to equation (4). However, equation (13) can be simplified further by the introduction of two dimensionless groups, U_{cap} (the capacity utilization) as defined by equation (6), and U_{c} (the utilization of covers) which is the proportion of time that the covers are actually used to the time that covers could be used and is described below.

Clearly, as throughput decreases, the potential to use covers increases and the proportion of time available to use covers will be (1-U_{cap}). However, covers may not be used for the entirety of this time, as other operational procedures need to be undertaken, such as drossing (removal of iron–zinc alloys from the molten metal) or replacing the zinc removed as part of the galvanizing process. Therefore, the proportion of time that covers are used will be

$$\frac{t_{\mathrm{c}}}{t_{\mathrm{total}}} = U_{\mathrm{c}}(1 - U_{\mathrm{cap}}) \tag{14}$$

Utilization U_{c} is zero when covers are never used and unity when covers are used for the entire time that the plant is not in production. In practice, most plants that use covers have a U_{c} value of around 0.3.

Substituting equations (6) and (14) into equation (13) produces the equation

$$\mathrm{SEC}_{\mathrm{demand}} = \hat{q}_{\mathrm{w}} + \frac{U_{\mathrm{c}} A_{\mathrm{s}}(\dot{q}_{\mathrm{s}} - \dot{q}_{\mathrm{c}})}{\dot{m}_{\mathrm{max}}} + \frac{U_{\mathrm{c}} A_{\mathrm{s}}(\dot{q}_{\mathrm{s}} + \dot{q}_{\mathrm{c}}) + A_{\mathrm{s}}\dot{q}_{\mathrm{c}}}{\dot{m}_{\mathrm{max}}} \frac{1}{U_{\mathrm{cap}}} \tag{15}$$

At the maximum production rate of the furnace, $\dot{m}_{\mathrm{max}}$, no covers are used, so that the equation for the demand for energy is described by equation (12). If $\dot{q}_{\mathrm{avg}}$ is the average heat flux through the walls of a kettle whose surface area is A_{HX}, then the maximum acceptable level of heat transfer can be described as

$$\dot{Q}_{\mathrm{demand,max}} = A_{\mathrm{HX}}\dot{q}_{\mathrm{avg,\,max}} = \hat{q}_{\mathrm{w}}\dot{m}_{\mathrm{max}} + A_{\mathrm{s}}\dot{q}_{\mathrm{s}} \tag{16}$$

and hence

$$\dot{m}_{\mathrm{max}} = \frac{A_{\mathrm{HX}}\dot{q}_{\mathrm{avg,\,max}} + A_{\mathrm{s}}\dot{q}_{\mathrm{s}}}{\hat{q}_{\mathrm{w}}} \tag{17}$$

An equation relating the average heat transfer to the critical heat transfer for the kettle wall can be developed. Computational fluid dynamics (CFD) work presented in reference [**22**] showed that the convection heat transfer was approximately constant along the wall. This allows the definition of the critical heat flux as

$$\dot{q}_{\mathrm{crit}} = h(T_{\mathrm{flame}} - T_{\mathrm{zinc}}) + \dot{q}_{\mathrm{rad}} \tag{18}$$

where $\dot{q}_{\mathrm{rad}}$ is the radiative flux from the flame.

The average heat flux can similarly be defined as

$$\dot{q}_{\mathrm{avg}} = h\left(\frac{T_{\mathrm{flame}} + T_{\mathrm{flue}}}{2} - T_{\mathrm{zinc}}\right) + \dot{q}_{\mathrm{rad}}\frac{A_{\mathrm{flame}}}{A_{\mathrm{HX}}} \tag{19}$$

where A_{flame} is the approximate area of kettle wall that is affected by significant radiation from the flame. This means that the area ratio in the last term of equation (2) is the total area of the furnace where flame radiation is significant compared with the total heat transfer area of the furnace. Experience of examining wear profiles on kettle walls and from validated CFD work shows that this area ratio term is roughly 45 per cent.

Parameter $\dot{q}_{\mathrm{rad}}$ is the radiation exchange between the flame and the kettle wall. The average radiation heat flux at the wall was calculated from the convection heat transfer using a radiation term, r_{rad}, which is the ratio of radiative to convective heat transfer. High-velocity furnaces have an average $r_{\mathrm{rad}} \approx 3.8$ [**22**].

Therefore, by dividing equation (2) by (1), substituting for $\dot{q}_{\mathrm{rad}}$ and simplifying, an expression for the average heat flux through the kettle wall in terms of the critical heat transfer and measurable parameters such as temperatures and heat transfer areas can be formulated

$$\frac{\dot{q}_{\mathrm{avg,\,max}}}{\dot{q}_{\mathrm{crit}}} \approx \frac{(1/2) + (T_{\mathrm{fHF}} - T_{\mathrm{zinc}}/2(T_{\mathrm{flame,HF}} - T_{\mathrm{zinc}})) + r_{\mathrm{rad}}(A_{\mathrm{flame,HF}}/A_{\mathrm{HX}})}{(1 + r_{\mathrm{rad}})} \tag{20}$$

For the two-burner furnace in question, this results in $\dot{q}_{\mathrm{avg,max}} = 13.7\,\mathrm{kW/m^2}$ which is lower than the critical heat flux of $29\,\mathrm{kW/m^2}$. Equation (20) can be defined as the ratio of the maximum heat transfer permissible to the average heat transfer in the furnace. Alterations to A_{flame} will need to be made if multiple burners are used. The effect of burner location on the flame length is described in reference [**23**].

Therefore, substituting equation (17) into equation (15), the $\mathrm{SEC}_{\mathrm{demand}}$ can now be defined as

$$\mathrm{SEC}_{\mathrm{demand}} = \hat{q}_{\mathrm{w}} + \frac{\hat{q}_{\mathrm{w}} U_{\mathrm{c}}(1 + (\dot{q}_{\mathrm{c}}/\dot{q}_{\mathrm{s}}))}{1 + (\dot{q}_{\mathrm{avg,max}}/\dot{q}_{\mathrm{s}})(A_{\mathrm{HX}}/A_{\mathrm{s}})} + \frac{\hat{q}_{\mathrm{w}}[1 - U_{\mathrm{c}}(1 + (\dot{q}_{\mathrm{c}}/\dot{q}_{\mathrm{s}}))]}{1 + (\dot{q}_{\mathrm{avg,max}}/\dot{q}_{\mathrm{s}})(A_{\mathrm{HX}}/A_{\mathrm{s}})} \frac{1}{U_{\mathrm{cap}}} \tag{21}$$

When covers are not in use, as when U_{cap} tends to unity, this reduces to

$$\mathrm{SEC}_{\mathrm{demand}} = \hat{q}_{\mathrm{w}} + \frac{\hat{q}_{\mathrm{w}}}{1 + (\dot{q}_{\mathrm{avg,\,max}}/\dot{q}_{\mathrm{s}})(A_{\mathrm{HX}}/A_{\mathrm{s}})} \frac{1}{U_{\mathrm{cap}}} \tag{22}$$

Equations (21) and (22) are of the form of equation (7) and fully describe the nature of the constants a and b for $\mathrm{SEC}_{\mathrm{demand}}$. Importantly, all the terms in these equations are independent of the production rate $\dot{m}$, shift pattern and, assuming the relation $A_{\mathrm{HX}}/A_{\mathrm{s}}$ is constant, furnace size. For most modern furnaces this ratio is 3.8. This is due to the galvanizer, who requires sufficient surface area and depth to permit the galvanizing of the maximum range of products for a minimum mass of molten metal. In general, the furnaces are long, narrow and deep. All the terms are thus functions of the furnace design.

These equations confirm the received wisdom within the industry that deep furnaces with a small surface area require less energy to operate. This also indicates that any work undertaken to increase the available heat exchange area or coefficient for the kettle would result in a furnace that would be able to provide the same demanded heat with a lower heat supply rate.

4 THEORETICAL ANALYSIS. PART 2: SUPPLY OF HEAT

In furnaces with two firing rates, high and low fire (HF and LF respectively), the supply to the furnace to meet the demand for heat can be defined as

$$\dot{Q}_{\mathrm{supply}} = \tau_{\mathrm{HF}}\dot{Q}_{\mathrm{supplyHF}} + \tau_{\mathrm{LF}}\dot{Q}_{\mathrm{supplyLF}} \tag{23}$$

The supply and demand are related by equation (2), where the temperature of the combustion gases at the flue leaving the furnace is used to calculate $\dot{Q}_{\mathrm{demand}}$ and $\dot{Q}_{\mathrm{f}}$. The proportion of time spent on high fire at any rate of demand can be calculated by the following equation

$$\tau_{\mathrm{HF}} = \frac{\dot{Q}_{\mathrm{demand}} - \dot{Q}_{\mathrm{demandLF}}}{\dot{Q}_{\mathrm{demandHF}} - \dot{Q}_{\mathrm{demandLF}}} \tag{24}$$

where τ_{HF} is the proportion of time spent at the high-fire setting of the furnace. A similar equation can be constructed for the proportion of time spent on low fire.

By substituting equations (21) and (24) and the definition of τ_{LF} into equation (23), an equation for $\mathrm{SEC}_{\mathrm{supply}}$ in terms of U_{cap} can be constructed

$$\begin{aligned}\mathrm{SEC}_{\mathrm{supply}} = {} & \left[\hat{q}_{\mathrm{w}} + \frac{\hat{q}_{\mathrm{w}}U_{\mathrm{c}}(1+(\dot{q}_{\mathrm{c}}/\dot{q}_{\mathrm{s}}))}{1+(\dot{q}_{\mathrm{avg,\,max}}/\dot{q}_{\mathrm{s}})(A_{\mathrm{HX}}/A_{\mathrm{s}})}\right] \\ & \times \left[1 + \frac{(\dot{Q}_{\mathrm{fHF}} - \dot{Q}_{\mathrm{fLF}})}{\dot{Q}_{\mathrm{dLF}}(m_{\mathrm{d}}-1)}\right] \\ & + \left[\frac{\hat{q}_{\mathrm{w}}[1 - U_{\mathrm{c}}(1+(\dot{q}_{\mathrm{c}}/\dot{q}_{\mathrm{s}}))] \times [1 + ((\dot{Q}_{\mathrm{fHF}} - \dot{Q}_{\mathrm{fLF}})/\dot{Q}_{\mathrm{dLF}}(m_{\mathrm{d}}-1))]}{1+(\dot{q}_{\mathrm{avg,\,max}}/\dot{q}_{\mathrm{s}})(A_{\mathrm{HX}}/A_{\mathrm{s}})}\right. \\ & \left. + \frac{\hat{q}_{\mathrm{w}}(m_{\mathrm{d}}\dot{Q}_{\mathrm{fLF}} - \dot{Q}_{\mathrm{fHF}})}{(A_{\mathrm{s}}\dot{q}_{\mathrm{s}} + A_{\mathrm{HX}}\dot{q}_{\mathrm{avg,\,max}})(m_{\mathrm{d}}-1)}\right]\frac{1}{U_{\mathrm{cap}}}\end{aligned} \tag{25}$$

where m_{d} is the ratio of demand on high fire and the demand on low fire, and is effectively the turndown of the furnace. As noted by the authors in reference [**20**], assuming that the air–fuel ratio is the same on both high and low fire, m_{d} will be approximately equal to the ratio of gas flowrates for high- and low-fire conditions.

If the plant is operating on a 24 h shift basis, so that the covers are not used, equation (25) reduces to

$$\begin{aligned}\mathrm{SEC}_{\mathrm{supply}} = {} & \hat{q}_{\mathrm{w}}\left[1 + \frac{\dot{Q}_{\mathrm{fHF}} - \dot{Q}_{\mathrm{fLF}}}{\dot{Q}_{\mathrm{dLF}}(m_{\mathrm{d}}-1)}\right] \\ & + \left[\frac{\hat{q}_{\mathrm{w}}[1 + ((\dot{Q}_{\mathrm{fHF}} - \dot{Q}_{\mathrm{fLF}})/\dot{Q}_{\mathrm{dLF}}(m_{\mathrm{d}}-1))]}{1+(\dot{q}_{\mathrm{avg,\,max}}/\dot{q}_{\mathrm{s}})(A_{\mathrm{HX}}/A_{\mathrm{s}})}\right. \\ & \left. + \frac{\hat{q}_{\mathrm{w}}(m_{\mathrm{d}}\dot{Q}_{\mathrm{fLF}} - \dot{Q}_{\mathrm{fHF}})}{(A_{\mathrm{s}}\dot{q}_{\mathrm{s}} + A_{\mathrm{HX}}\dot{q}_{\mathrm{avg,\,max}})(m_{\mathrm{d}}-1)}\right]\frac{1}{U_{cap}}\end{aligned} \tag{26}$$

The furnace efficiency has already been defined in equation (3) as the ratio of heat demand to heat supply. This can now be solved algebraically using equations (21) and (25), which allows the calculation of furnace efficiency over the full range of its capacity utilization.

The equation for $\mathrm{SEC}_{\mathrm{supply}}$ indicates the key factors in the energy consumption of a galvanizing furnace. These are:

Production values	U_{c} and $\dot{q}_{\mathrm{c}}$
Independent values	$\hat{q}_{\mathrm{w}}$, $\dot{q}_{\mathrm{s}}$ and $\dot{q}_{\mathrm{crit}}$
Geometric considerations	A_{HX}, A_{s}
Combustion considerations	$\dot{Q}_{\mathrm{supplyHF}}$, $\dot{Q}_{\mathrm{supplyLF}}$, T_{fHF}, T_{fLF} and A_{flame}

The supply of heat both on low fire and on high fire is dependent on the mass flowrate supplies of fuel and combustion air. Combined with the flue temperature information on high and low fire, the values for demand heat supply and the demand turndown can be calculated. From these twelve values it is possible both to calculate and to optimize the energy consumption of a galvanizing furnace.

5 VALIDATION OF EQUATIONS WITH ENERGY CONSUMPTION DATA

Flue gas analysis of an existing galvanizing furnace permits the use of equation (25) for the calculation of the theoretical energy consumption and the thermal efficiency of the furnace. A brief summary of the data recorded in the field is presented in Table 1. The calculated values for *a* and *b*

Table 1 Summary of field data from the furnace used for validation

	High fire	Low fire
Gas flowrate (m^3/h)	67.42	4.37
T_f* (°C)	517	430
Xair† (% greater than stoichiometric)	41.8	128.2

*Values taken using continuous data logging equipment.
†Values taken from flue gas analysis.

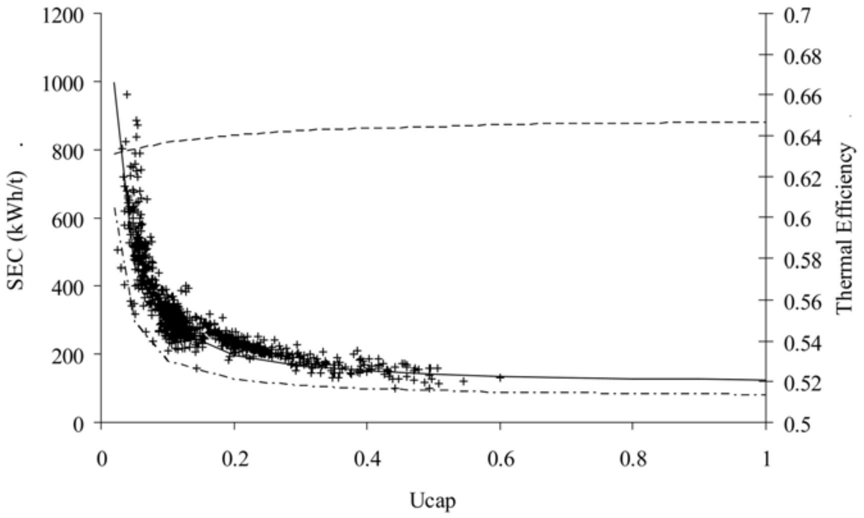

Fig. 3 SEC predicted by equations (21) and (25) compared with furnace gas consumption data

can then be compared against energy consumption information taken from readings of the furnace gas meter and production records of the plant, as shown in Fig. 3 for a furnace where the turndown, m_d, is approximately 17.

The shape of the thermal efficiency curve is contrary to that expected, in that it increases both with U_{cap}, and with extended periods of high fire rather than decreasing as described above and in reference [**10**]. This is because the excess air required at the low-fire setting is substantial and results in the cooling of the furnace as the bulk gas temperature is below the zinc temperature. This can be seen in Table 1 as the flue exit temperature is lower than the operating temperature of the furnace. In this case, the efficiency of the furnace will be increased by minimizing the proportion of time spent on a low-fire setting. It is clear that the performance of the furnace would be improved if the excess air levels at low fire could be reduced.

6 IMPLICATIONS FOR FURNACE DESIGN

If the complication of high levels of excess air can be resolved, a greater proportion of time spent at the low-fire condition would result in higher levels of efficiency. This is due to the flue temperature at the low-fire condition being closer to the operating temperature of the furnace.

The optimum setting for the high- and low-fire levels would be such that at $U_{cap} = 0$, $\tau_{LF} = 1$ and at $U_{cap} = 1$, $\tau_{HF} = 1$. If these two conditions are fulfilled, the furnace supply will be correctly balanced for the demand.

If the turndown were any lower than the balanced turndown, described in the previous paragraph, the furnace would provide too much heat to the kettle at low utilizations, and the zinc temperature would then slowly increase, an effect known as creep. This is highly undesirable as continued creep will result in the tripping of the high zinc temperature alarm. In such an event, the furnace will be shut down,

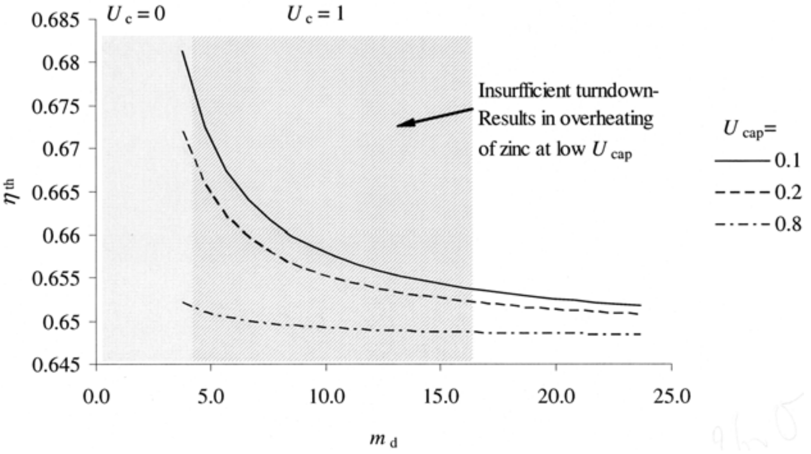

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Fig. 4 Effect of increasing turndown on thermal efficiency at various levels of U_{cap} (T_{fLF} assumed to be 450 °C), showing regions resulting in overheating with or without covers

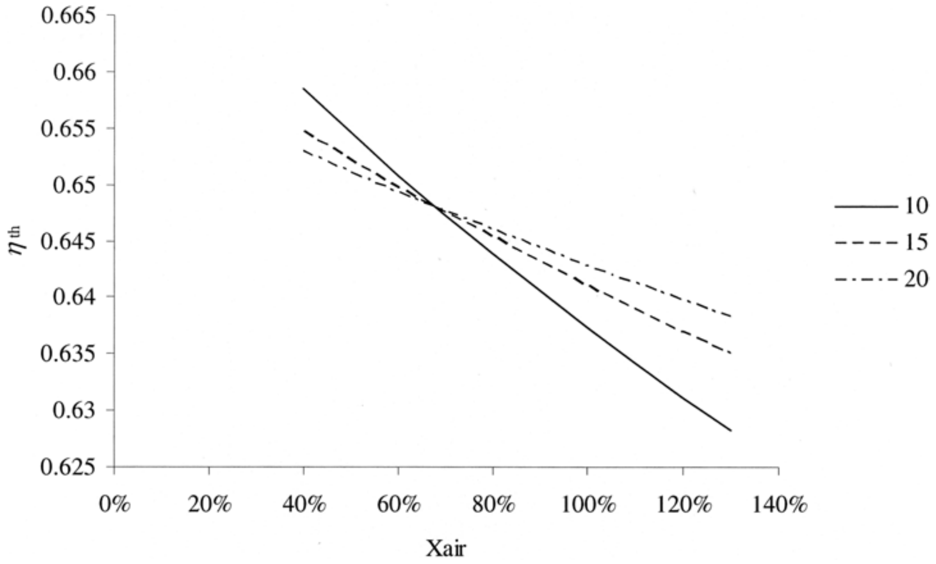

Fig. 5 Effect of excess air on thermal efficiency for various turndown ratios at $U_{cap} = 0.1$ ($U_c = 0.3$, $T_{fLF} = 450\ °C$)

followed by an air purge of the combustion gallery, resulting in high levels of inefficiency as the cold air cools the combustion gallery and the zinc melt. If the turndown is increased so that at $U_{cap} = 0$, $\tau_{LF} < 1$, more time will be spent on high fire, resulting in higher flue temperatures. The resulting drop in efficiency can be seen in Fig. 4.

Assuming that the low-fire flue temperature is 450 °C and covers are used, the turndown of the system only needs to be able to supply heat between the maximum demand at $\dot{m} = \dot{m}_{max}$ and the minimum demand at $\dot{m} = 0$, so that the minimum demand is solely to replace the energy lost from the surface of the molten zinc through the covers

$$m_d = \frac{\dot{Q}_{demandHF}}{A_s \dot{q}_c} \tag{27}$$

For the furnace in question, if no covers were used the demand turndown would reduce to $m_d \approx 4$. If covers were to be used, a demand turndown of $m_d \approx 16$ would be desirable.

This all assumes, of course, that the excess air problem can be resolved. If this is not the case, turndown should be increased as far as possible so that more time is spent on high fire as shown in Fig. 5. Once the excess air is greater than approximately 70 per cent, the efficiency of the furnace at low utilizations is improved at high turndown ratios in comparison with lesser turndown ratios.

However, in comparison with a system with a moderate turndown and improved stoichiometry, the wastage of gas energy using a high turndown and excessive excess air can clearly be seen in Fig. 6. As can be seen, the resulting decrease in efficiency may negate the benefits of developing high-turndown burners; a much more prudent focus of effort would be the design of a burner with a turndown of, say, 1:16, with no significant increase in excess air consumption.

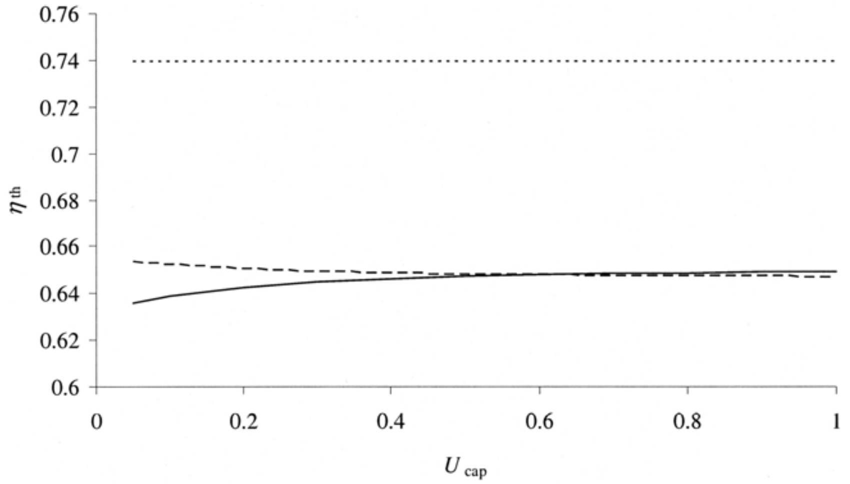

Fig. 6 Comparison of thermal efficiency between actual furnace performance and various improved cases ($U_c = 0.3$)

The idealized case shown in Fig. 6 assumes that the flue gases for both high- and low-fire cases are at 450 °C, which should result in the highest possible thermal efficiency for a combustion furnace operating at 450 °C—approximately 74 per cent. This assumption of a minimum flue temperature also affects the calculation of the maximum throughput of the furnace, as the temperature term in equation (20) equals 0.

Reduction in excess air as shown in Fig. 6 would result in a decrease in gas consumption. At $U_{cap} = 0.1$, the SEC_{supply} would decrease from 338 kW h/t to 314 kW h/t for the actual and balanced, reduced excess air furnaces respectively. By reducing the time spent on high fire, the life of the kettle will be extended, as the maximum heat flux is reduced.

7 CONCLUSIONS

A set of equations has been presented that describes the energy efficiency of a galvanizing furnace. These equations can be non-dimensionalized to provide a description of furnace efficiency. Equations of this form can be used for comparing furnaces of different designs and fuel types in a completely objective fashion. This removes the reliance on production rates, which have characterized previous work on furnace energy consumption.

If the excess air quantity at the low-fire setting is reduced to below 70 per cent, the turndown need not be as extreme as current designs require. This will make burner manufacture and set-up easier, and also reduce the energy consumption of the furnace.

This is the first approach using SEC_{demand} and SEC_{supply} to describe thermal efficiency. It can lead to the useful analysis and non-dimensional comparison of other processes where the heat demand during idling conditions (U_{cap} tends to zero) is important and cannot be addressed by increasing the turndown to a maximum.

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