Optimising the compromise in galvanizing furnaces

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ABSTRACT

The first stage technology evolution of indirect heating systems for galvanizing was driven by the availability and cost of fuels. This paper tracks this development with an explanation of how and why systems have changed and the drive for more environmentally acceptable heating methods. After an outline of the realities of operating heating systems, the divergence between theory and practise will be illustrated. With the galvanizing industry largely copying developments in heating systems within steel operations, the background to the need for pulse fired systems becomes clear. Such systems (double and triple fire) provide for the precise control required to maximise permissible heat efficiency. This technology has allowed the second stage of evolution, performance interrogation via digital interfaces. These opened the opportunity for comprehensive algorithm development. Past the use of Human Interface controls, mobile internet usage now allows for real-time monitoring and control from remote locations, the development of large databases by suppliers to further refine designs and controls and, economic (efficiency) benefits for the galvanizer. Challenges still exist and possible future developments will be explored.

INTRODUCTION

By its nature, a galvanizing plant spends much of its economically active time in an unsteady state. In a batch process, the application of steady state assumptions and laws whilst providing guidance can lead to unmet expectations for the galvanizer.

Theoretically, the objective of galvanizing is clear – have a mass of molten zinc heated with minimum fuss such that an article can be dipped into the zinc and gain a protective coating. Looking at things simply, there would appear to be three things to balance in designing the heating system for a kettle:

1. The size and shape of the kettle and furnace should be optimized to keep the heat requirement to the absolute minimum required. Most of the undesirable heat losses are from the surface of the kettle so this should be kept to the minimum required and the kettle should be used to capacity
2. As much of the calorific value of the fuel should be used to heat the zinc in the kettle. It should be noted that, overall the higher the calorific value of the fuel the easier it is to control.
3. The heat has to be applied in such a manner to minimize kettle heat stress in terms of the kettle wall and maintain a minimum variation in zinc temperature during the dipping process to avoid issues relating to local temperatures resulting in excessive dross, ash and scale production on the kettle walls (internally and externally).

A simple assessment of the above factors immediately shows that there are a series of compromises to be made when operating a galvanizing kettle.

HEAT INPUT REQUIREMENTS

Referring to various references the following numbers may be used to calculate the heating requirements when using a kettle [1, 2].

- Heating steel to 450 °C requires around 55 kW per tonne
- Melting the zinc to 450 °C requires around 82 kW per tonne

So, theoretically 66kW is required to heat the steel and melt out the replacement zinc but,

- Evaporating water takes 1.1 kW per tonne (assuming 20g water per m^2 of steel surface).
- Heat losses by radiation and convection can be up to 17kW/h per m^2 of kettle surface and 1kW/h per m^2 of unheated kettle surface. This latter number indicates why a proper fitted, insulated cover should be used during idle times.
- There is also heat lost through ash removal.

In total some 70 kW is required per tonne of steel galvanized, although this figure will vary according to the kg/m^2 of steel, actual zinc pick-up etc. However, what is clear is that high tonnages will increase thermal needs and so thermal stresses across the board.

The greatest heat loss is through the surface when articles are dipped. This is why some furnace designers feel that a double furnace chamber system should be used. Indeed even 75 years ago it was suggested that 2/3 of the heat should be applied to the top half of the kettle, 1/3 to the next quarter and little if any applied to the bottom quarter [1].

The maximum heat flux should not exceed 24 – 29 kW/m^2. This should prevent the inner kettle wall reaching a temperature greater than 490 °C where accelerated attack of the kettle walls by the zinc is well underway **(Figure 1.).** Galvanizers want enough surface area and depth to permit the galvanizing of the maximum amount of product for a minimum mass of molten metal. So in general furnaces are long, narrow and deep. Good furnace design should minimise vertical thermal gradients which would limit heat transfer and so capacity.

ENERGY AVAILABILITY

Energy inputs for galvanizing have broadly followed industrial progress. Solid products such as coal and coke have been used and gas has been produced from both. Oil has and, in some areas, is still used. Electricity is widely used but many plants now use gas in its various forms. This paper focuses upon gas fired furnaces and as such electrical heating is not considered. However, it is always important to ensure that, when comparing heating fuel costs, the actual calorific value of the various fuels are compared to get realistic fuel running costs and ensure that burner and other requirements are tailored accordingly.

What is often not understood is that the evolution of furnaces has walked largely hand in hand with gas supply development – both quantity and quality. So there has been coal gas which was really the old town gas. It was rich in sulphur and ammonia and had variable calorific value. As the main market was for illumination the presence of hydrocarbons to produce soot and visible flames was important but this reduced the calorific value. Other gas types have been water gas (CO and H_2), producer gas (similar to water gas but contains N_2 and hydrocarbons and was used in China in some areas until quite recently), wood gas, oil gas and now natural gas. It's worth noting that many of these gases had a much higher calorific value than many natural gasses but they were polluting and had inconsistent properties from batch to batch. It's the cleanliness and consistency combined with overall availability that has allowed natural gas to become preeminent and so permit adoption of gas furnace heating on a wide scale.

Relying upon the combustion of carbon means that:

1. The calorific value of the various fuels available is determined by the ease and nature of the energy release in burning carbon with oxygen.

2. The greater the surface area in contact with the oxidizing agent (generally air) the more efficient heat generation will be. That is why burner manufacturers have the mantra of temperature (high enough to maintain ignition), turbulence (to ensure intimate mixing of fuel and oxygen) and time (sufficient for complete combustion).

3. Liquids such as oil are easier to control and are more efficient than (say) coal and the use of gas should be even easier to control and more efficient still as atomization is not required as with liquids. One should also be aware of the polluting nature of some fuel oils.

The oxidizing agent is generally air which, of course, has to be heated and contains 80% nitrogen which does nothing other than absorb heat and produce NOx. Heating the air through the burner is another source of heat requirement and generally, a small excess of air is required to ensure complete combustion and avoid smoke or soot. Until around 50 years ago typical burner efficiencies were around 30%. With the oil price shock, the furnace industry started to use heat recovery (recuperative – or outside, regenerative – inside the furnace) to pre-heat the combustion air and increase burner efficiencies up to 60%.

In an ideal world maximum furnace efficiency with gas is achieved when the temperature of the gas exiting the flue system is just above 450 °C. This is irrespective of high or low turn-down rates and has some assumptions concerning excess air used in combustion at low fire rates.

Once hydrocarbon gases are used water vapour is generated as a product of the combustion process and this adds another level of complexity in terms of the need to avoid condensation within the after furnace flue chimney system.

Using a generalised combustion equation, the point where all oxygen is consumed and all fuel burned is defined as the stoichiometric point (SP) **(Figure 2)** [3]. This can be seen from the equation below –

$C_mH_n + (m+n/4)O_2 \rightarrow mCO_2 + (n/2)H_2O$

and specifically for methane -

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ + heat

The SP is the air to fuel ratio which gives complete combination of the gas and the oxygen in the air to form carbon dioxide (CO_2) and water (H_2O). Ideal operation occurs at the SP. Operation to the left of the SP results in incomplete gas combustion and production of carbon monoxide (CO), with a greatly lowered efficiency, and presence of unburned gas in the flue gas. Operation to the right of the SP results in excess air which is heated by the flame. Heat is carried out in the flue gas, resulting in efficiency loss. The excess oxygen also results in an increase in NO_x production. The highest efficiency occurs in the zone directly to the right of the SP.

THE DEVELOPMENT OF INDIRECT HEATING GAS FURNACES

Indirect heated gas furnace design has largely been led by developments in the steel industry. Furnaces are used for many heat treatment processes in steel production and galvanizing heating systems have been fast followers of this technology development.

The simple use of the hot gases results in the best form of heating but a key issue is how best to circulate the gases? Initially gases were forced around the furnace area using a fan and whilst uniform temperature over the kettle heated surface with no over-heating are possible, inefficiencies remain and the fan systems require regular maintenance and take up space.

The three key issues to be overcome with indirect heating by gas are:

1. Poor temperature uniformity within the furnace which would impact upon kettle life and heat use efficiency.

2. Inadequate turn-down. Initially heating burners were switched on and off to control heat inputs. This resulted in excessive maintenance and reliability issues with burner systems. By having a high fire and low fire mode, issues of poor combustion and some complexity and maintenance issues are addressed but only if low fire is low enough to avoid overheating.

3. Excessive fuel consumption was an issue with early furnace systems. Increasing energy prices and just the need to get better control of things has resulted in the modern furnace systems we see today.

A high velocity pulsed flame system whereby heated air is driven around the furnace chamber with sufficient mixing to ensure temperature uniformity within the chamber may be considered to be the most efficient option for heating. The key advantages of such as system can be listed as:

- Enough thermal capacity to meet the maximum demanded production rate. The kettle can be sized to the production rate in tonnes/hour, not compromised to suit work dimensions. The burner operating output can be optimized to the demand.
- Flexibility to control the system to a constant zinc temperature. A highly variable heat input can be provided through the use of control systems. So, temperature can be controlled to within a few degrees without overshoots and fuel/gas control is relatively simple.
- Low maintenance is achieved through the minimal numbers of burners required - unlike flat flame. Simple control and minimal moving parts, such as recirculation fans, means that kettle lives can be extended to over 10 years.
- Maximum Fuel Efficiency can be achieved through using appropriate flue temperatures when compared with flame temperatures, the high velocity system ensures uniform convection of heat and direct heating of the entire kettle maximizes heat transfer.
- The simplicity of the system means that there is a low cost civil engineering outlay, there are a few burners and they are located at ends of furnace, no access is required along the furnace length, unlike flat flame systems, so furnace chambers can be narrow. Overall there is a lower hardware cost on combustion equipment, both flow gear and electrical equipment and this lends itself to packaged designs requiring a few days for installation before melt out can commence.
- Better environmental performance due to accurately pre-set fuel/air ratios which ensure complete combustion. NOx emissions are minimised as the high velocity flame entrains more furnace gases through complete mixing and lower peak temperatures than alternative systems.

BURNER CONTROLS

Initially, burner (and so flame) control was simply managed through adjusting the flow of gasses as part of a feedback system reacting to kettle temperature. This type of analogue control often resulted in temperatures over and under shooting the ideal beyond a reasonable excursion. This form of modulation control is not ideal.

Probably the final area of pure engineering development in high velocity flame systems was the introduction of preset systems. With modulation control the fuel is controlled to provide for a variable heat flame. It is important to bear in mind that it is the flow of hot gasses along the furnace gallery that ensure that an even flue gallery temperature is achieved within a short distance from the flame. There is no direct flame onto a kettle surface. With a pulse firing regime, the flame is either on maximum (high-fire) or a low value (low-fire) generally dictated by the burner. High turn-down rates (the ratio of high to low fire) are targeted to ensure that the resulting furnace gallery exit temperature remains above 450 ℃. Pulse firing is not simple high fire/low fire as high/low fire systems would have high firing for as long as it takes to return the zinc temperature back to its set value. This generally results in temperature overshoot. Pulse firing on the other hand is a set on a high/low timing sequence which is preset for the furnace capacity. The variable time on high fire provides for full kettle heating within the overall design of the system. This results in more even and consistent heating along the walls of the kettle. Only two settings of air and fuel are required which greatly improves the efficiency and ease of operation.

By controlling the high fire pulse times sufficient heat can be sent to the furnace gallery – shown in the lower graph of **Figure 3**. Although there would appear to be some hysteresis in gas temperature, the kettle wall has sufficient thermal capacity to dampen the variations in furnace gallery temperature. So the protective zinc alloy layers on the inside of the kettle wall are not stressed by the gas temperature variations at all. At high fire, the velocity of the flame can reach 170m/s. This adds sufficient velocity to the gas in the gallery to ensure active scrubbing of the whole kettle surface which improves even heating along the kettle surface.

Further environmental pressures are beginning to bear down on the furnace industry. Simple aspirator burner nozzles are being replaced with nozzle mix burners and electronically controlled mass-based variable mixers which allow real time control over the air-fuel ratio, based on measurement of the flue gas composition and other parameters.

Flue Gas Recirculation (FGR) can lead to cooling of the flame to reduce NOx to <9ppm. MFT involves pre-mixing fuel and air and stabilizing the flame on a metal-fibre material. Surface stabilized combustion stretches the flame, eliminates hot-flame zones and reduces thermal NOx formation within the flame and this can get to <9ppm without using FGR. However, metal-fibre burners typically require excess air levels of 50-60%.

Finally, it should be mentioned that the steel furnace industry is starting to experiment with Fuzzy Logic controllers for high velocity pulse burner control based upon Mamdani's models [(4)]. This certainly flattens the outside of kettle variations in temperature and will be the way forward very soon.

FURNACE CONTROL AND MANAGEMENT SYSTEMS

With all the above developments in play, it is clear that software enhancements should ensure fine tuning to gain not only greater efficiencies but also easier management control.

Control and management systems now allow for:

- The maintenance of the optimum (sometimes pre-set) air/fuel ratios for the desired heat output. This is set by process controllers to achieve full combustion and uniform heat transfer from combustion products via the kettle to the work-pieces. Studies have shown that where large kettles are used and rarely reach full production capacity a lower High Fire Pulse can save at least 2% of gas costs. This additional (third) set-point is easy to introduce and control with current software.
- The control of deviations in air & fuel temperatures and pressures and furnace chamber pressures to fully trim the air/fuel ratio and ensure full burner turn-down.
- Remote servicing and control which is now possible via internet connections and mobile devices. Open source and in-house network architectures provide for secure, remote supervision & diagnosis.

CONCLUSIONS

It is clear that the use of pulse fired, high velocity burner systems should provide the optimum furnace installation for hot-dip galvanizers. The current state of understanding of such systems has developed such that rigorous control is possible to really optimize energy utilization in the dipping process. The development of software algorithms enables the galvanizer to be guided in such a way as to make the best use of the furnace in terms of ensuring long kettle life and operating with sound practice. Further automation is now possible along the whole galvanizing process and the use of “big data” is providing enhancements more rapidly than can be absorbed. However, galvanizing remains as stated in the introduction, a process in unsteady state. As a result, there remains no substitute for having galvanizers who are well versed in the theory and art of galvanizing.

References

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3. Rycroft, M. The importance of proper gas combustion control. EE Publishers, May 2018.
4. Cadena-Ramirez, et. al. Modelling and simulation of furnace pulse firing improvements using fuzzy control. Transactions of the Society for Modelling and Simulation International, 2017.

Figures

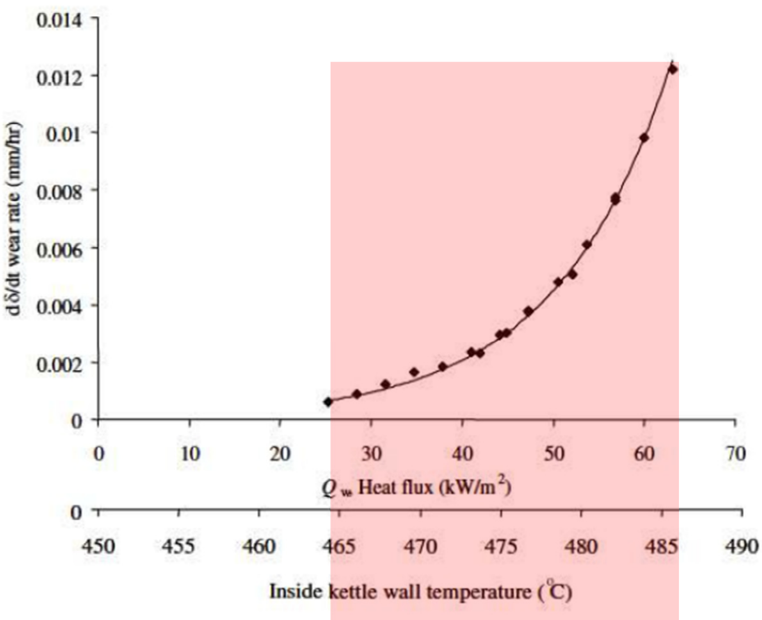

Figure1. Kettle wear rates for various heat flux and internal kettle wall temperatures.

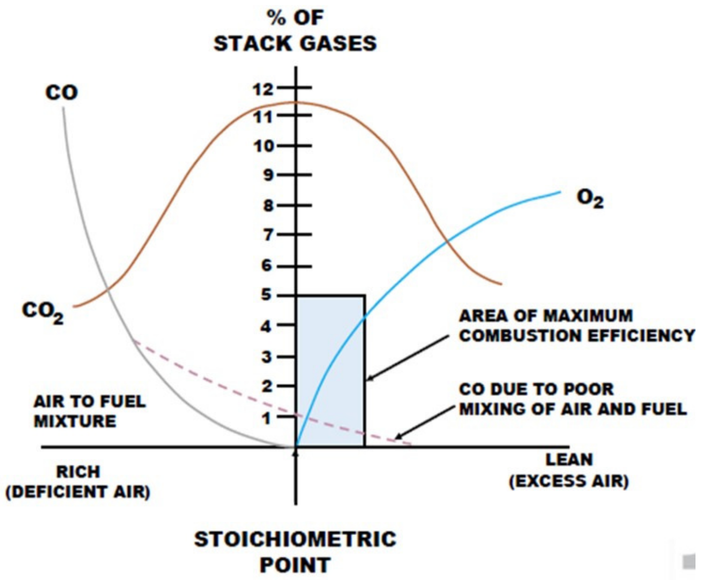

Figure 2. Ideal stoichiometric combustion point for gas fuels.

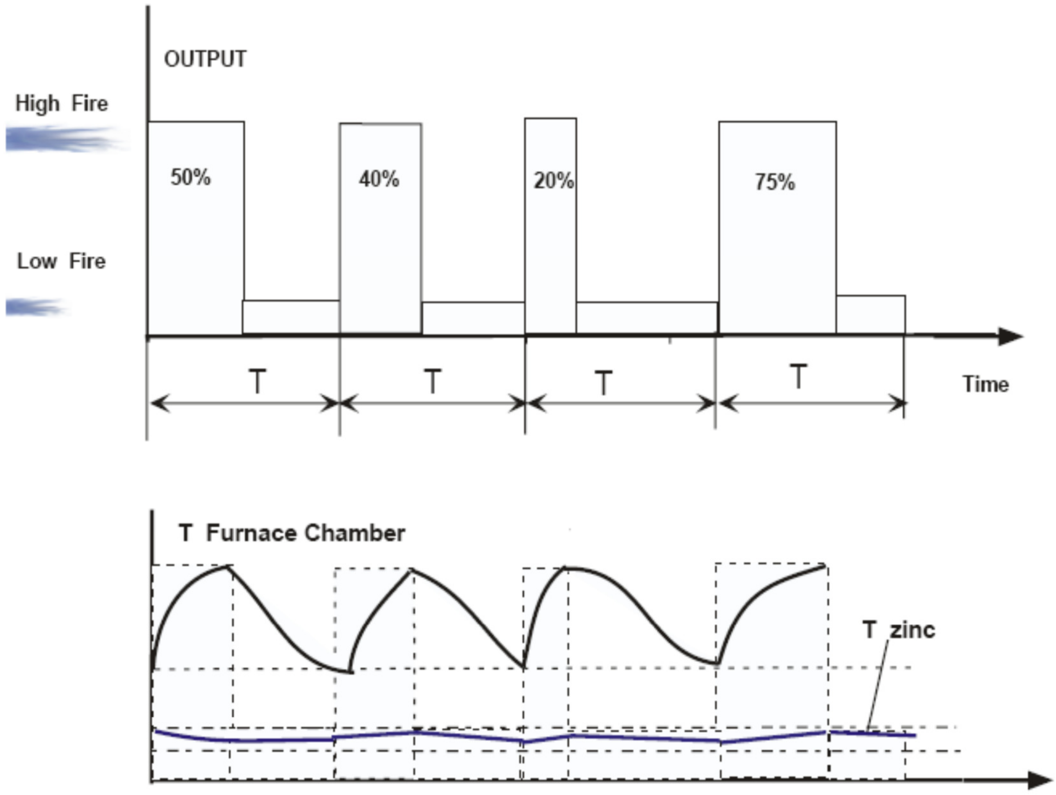

Figure 3. Typical High Fire, Low Fire and resultant furnace temperature