# EFFECT OF CONTROL SYSTEM DESIGN ON THE FUEL EFFICIENCY OF A FLUIDIZED BED HEAT TREATING FURNACE

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## ABSTRACT

Fluidized bed annealing furnaces used for annealing low- and medium-carbon wire products have been used for a number of decades as an environmentally friendly alternative to more traditional heat treating systems based on molten lead. Recent investigations into heat transfer rates to wires immersed in a fluidized bed have shown that the heat transfer rate is relatively constant over a wide range of fluidizing rates, contrary to earlier thinking. As a result, it is possible to modulate air/gas flow rates in these systems without affecting product quality due to variable heat transfer rates. Typically, systems have operated at constant fluidizing air flow rates with either on/off gas control, or modulating gas only, resulting in high effective excess air operation and resulting low thermal efficiency. This work investigates the result of operating a fluidized bed with modulating air/fuel flow rates at fixed air/fuel ratios, resulting in improved thermal efficiency. Results indicate that significant fuel savings can be achieved, particularly at lower load levels.

# EFFET DE LA CONCEPTION DE SYSTÈMES DE CONTRÔLE SUR L'EFFICACITÉ DE CARBURANT D'UN FOUR POUR LE TRAITEMENT THERMIQUE A LIT FLUIDISÉ

## RÉSUMÉ

Pendant plusieurs décennies, les fours à recuire à lit fluidisé ont été utilisés pour le traitement thermique des fils à faible et moyenne teneur en carbone comme alternative pour le traitement thermique traditionnel des systèmes basés sur le plomb fondu. Les recherches récentes sur les taux de transfert de chaleur des fils immergés dans les fours à recuire à lit fluidisé ont montré que le taux de transfert de chaleur est relativement constant sur un large éventail de taux fluidification, contrairement à ce qui est pensé. En conséquence, il est possible de moduler le débit d'air/gaz dans ces systèmes sans affecter la qualité du produit due aux taux transferts thermiques variables.

Typiquement, les systèmes qui opèrent à des débits d'air de fluidification constants avec contrôle de gaz Marche/Arrêt, ou seulement avec la modulation du débit de gaz, possède une grande efficacité d'opération d'air excessif et une faible efficacité thermique.

Le but de ce travail est d'étudier le résultat de la combinaison d'un lit fluidisé avec la modulation des débits d'air/carburant à des ratios air /carburant fixes pour améliorer l'efficacité thermique. Les résultats obtenus indiquent que des économies significatives de carburant peuvent être réalisées, particulièrement si les niveaux de charge sont bas.

## INTRODUCTION

Fluidized bed annealing furnaces have become increasingly popular in the steel wire manufacturing industry as they are the most viable alternative to lead annealers, which have become difficult or impossible to install in many jurisdictions due to stringent environmental regulations [1]. The lead annealer, used for many years for heat treating steel wire, rod and strip, uses an open bath of molten lead held at annealing temperatures to heat product immersed in it. Though molten lead is a highly efficient heat transfer media, issues associated with its toxicity and environmental contamination has severely restricted its use in recent years. Though the fluidized bed is an attractive alternative to lead, it has some inherent limitations, particularly with respect to fuel consumption at light loads. This limitation has arisen from the belief that it is necessary to operate the fluidized bed at a fixed fluidizing rate to ensure that uniform heat transfer conditions are created. It was thought that varying the fluidizing rate would affect the heat transfer rate to immersed wires, resulting in variable product quality. This belief stemmed from research into heat transfer to immersed cylinders conducted over the past several decades. This work, summarized by Saxena in [2], clearly showed that the heat transfer rate to an immersed cylinder increased as the fluidizing rate increased. However, all of this research was based on experiments involving heat transfer to tubes 12.7mm diameter and larger, in the context of boiler tubes immersed in coal-fired fluidized beds used for power generation. Virtually no work has been reported on smaller cylinder sizes appropriate to steel wire. Recent experiments conducted at Ryerson University, reported in [3], have shown that this trend breaks down below approximately 10mm diameter in fluidized beds of aluminum oxide in the 50 – 90 grit size range (145 - 330 μm). In fact, it has been shown that the heat transfer rate to wires in a fluidized bed is essentially constant beyond a fluidizing rate of $U/U_{mf} > 2$, where $U_{mf}$ is the minimum fluidizing gas velocity required for fluidization and U is the actual fluidizing gas velocity. This is clearly illustrated in Figure 1, which shows actual Nusselt number data for a 3.18mm (1/8") wire immersed in a 60 grit (250 μm) fluidized bed. The figure also shows correlation predictions for the same size wire under the same conditions. Clearly, these correlations [1], all derived from data for heat transfer to immersed tubes in the 25 – 50mm diameter range, cannot be used to accurately predict the heat transfer rate to wire-sized cylinders. A new correlation, suitable for use with wires, has been developed and is reported in [3]. This correlation has been used in all calculations presented herein. One of the main implications of this finding is that the fluidizing rate in a fluidized bed can be varied over a fairly wide range without affecting the heat transfer rate and hence product quality.

While the calculations set out in this work are specific to the heat treatment of wires in a fluidized bed, the principals can be extended to other systems as well. Recent work has shown that heat transfer rates to flat strips (often annealed in lead) immersed in a fluidized bed also remain essentially constant beyond around 2 x $U_{mf}$ for all orientations tested [4], and hence the arguments developed herein would apply equally to the heat treatment of strip.

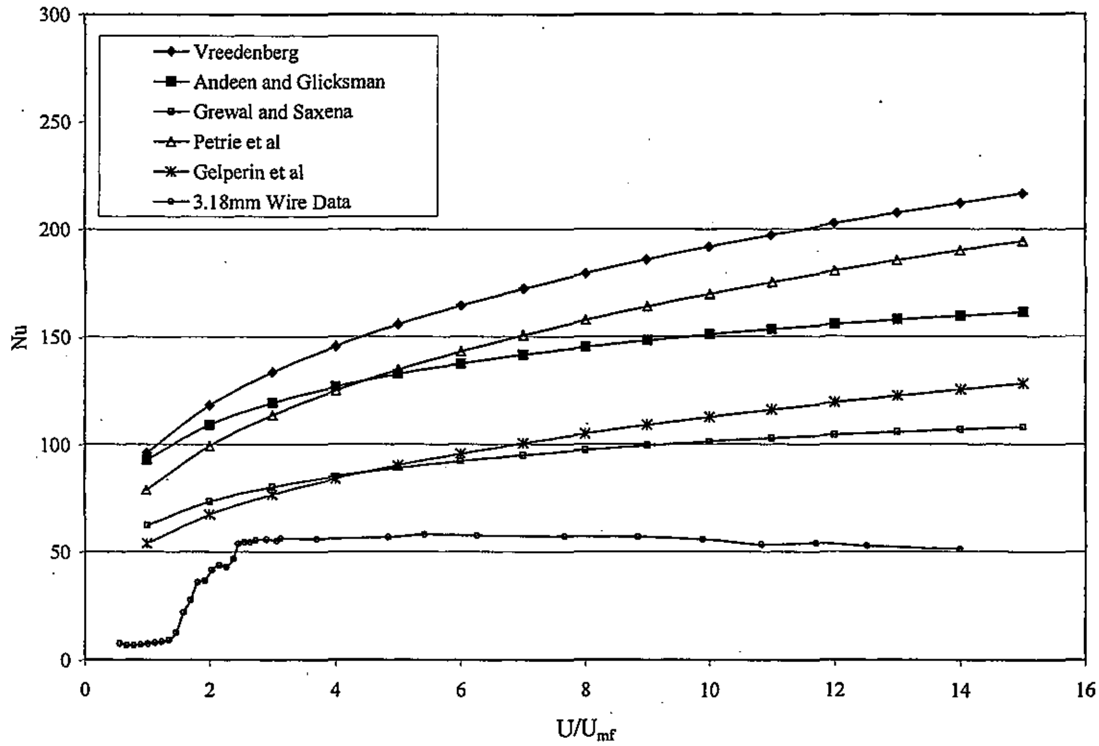


**Figure 1:** Comparison of standard correlations to data for heat transfer to a 3.18mm wire in a fluidized bed (from [2])

## DISCUSSION

Most fluidized beds used for continuous heat treatment of wires are set up using three or more zones of control. Figure 2 shows a typical cross-section of a fluidized bed heat treating furnace. Each zone has its own temperature control system, but typically all zones are of the same length and are set to the same or nearly the same temperature and fluidizing rate. Cold wire enters the furnace at Zone 1, where large amounts of heat are absorbed as the temperature difference between the wire and bed is large. The wire then passes to Zone 2, where proportionately less heat is transferred to the wire as the driving temperature difference between the bed and wire is less, and finally enters Zone 3, where even less heat is absorbed. If the furnace has been properly designed, the wire will reach annealing temperature in Zone 3, and then exit the furnace for quenching and further processing. Typically, the fluidizing air flow to each zone is similar, and temperature is controlled either by modulating the gas or using an on/off (time proportioning) gas control, while maintaining continuous air flow. Usually, the procedure used to size the fluidized bed and determine the air flow rate to each zone is as follows:

1) Determine the total immersion time required for the product to reach the desired annealing temperature:

$$t = \left(\frac{\rho}{h_c}\right)\left(\frac{V}{A_s}\right)\int_{T_i}^{T_f}\frac{Cp(T)}{(T_\infty - T)}dT \qquad (1)$$

where: $\rho$ = Material density (kg/m$^3$)
$h_c$ = Convection coefficient (W/m$^2$-K)
$\frac{V}{A_s}$ = Volume to surface area ratio (m)
= d/4 for cylinders of diameter d
$= \frac{wt}{2(w+t)}$ for strips w wide x t thick
$T_i$ = Material initial temperature (K)
$T_f$ = Material final temperature (K)
$T_\infty$ = Furnace temperature (K)
Cp = Material specific heat (J/kg-K)

2) Determine the time of immersion per zone by dividing the total time to reach the desired temperature using Equation 1 (plus any soak time if required) by the number of zones.
3) Determine the inlet and exit temperature per zone using Equation 1 and the immersion times per zone.
4) Determine the heat loading per zone using the following:

$$Q_{zone} = \dot{m}\int_{T_{in}}^{T_{out}} Cp(T)dT \qquad (2)$$

where: $\dot{m}$ = Material mass flow rate (kg/s)
$Q_{zone}$ = Zone heat loading (W)
$T_{in}$ = Zone material inlet temperature (K)
$T_{out}$ = Zone material outlet temperature (K)

5) Determine the required fuel input to Zone 1 based on the Zone 1 heat loading, any expected losses, the fuel HHV (typically 55 MJ/kg) and the available heat for the furnace operating temperature $T_\infty$ and desired excess air (typically 5 - 10%) [5][6]:

$$\dot{m}_{fuel,zone1} = \frac{Q_{zone1} + Q_{losses}}{\eta \cdot HHV_{fuel}} \qquad \dot{m}_{air} = \dot{m}_{fuel,zone1}(A/F)_{stoich}(1+XS) \qquad (3)$$

where: $\dot{m}_{fuel,zone1}$ = Mass flow rate of air to Zone 1 (kg/s)
$Q_{losses}$ = Zone heat losses through walls, openings etc (W)

$\eta$ = Available heat (from charts [6])
HHV = Fuel higher heating value (J/kg)
$\dot{m}_{air}$ = Air mass flow rate (kg/s)
$(A/F)_{stoich}$ = Stoichiometric air/fuel ratio by mass
XS = Excess air

The air mass flow rate determined from the above will then be used for all zones so that all zones will have the same fluidizing rate. However, since the heat loads in zones 2 and 3 will be lower, less fuel will be required, resulting in these zones running at higher levels of excess air due to reduced flow rate (or equivalently, gas switched off for portions of the operating time).

6) Based on the product speed, number of parallel wires and other physical considerations determine the physical size of the furnace and each zone. Based on this, determine the appropriate sand particle size such that the zone air mass flow rate determined using Equation 3 provides a reasonable fluidizing rate on the order of 3 – 5 x $U_{mf}$.

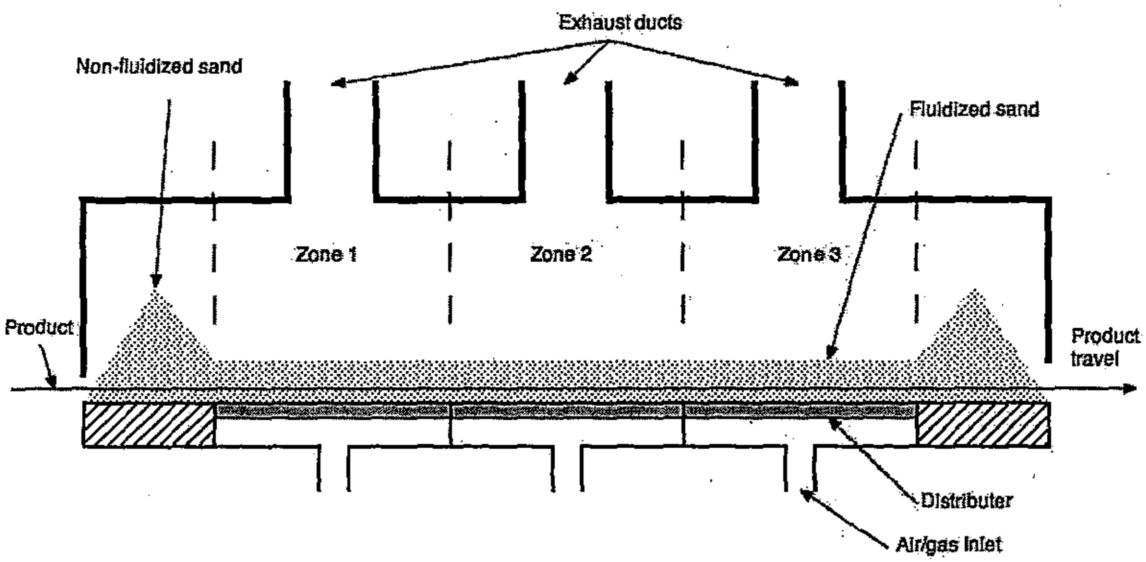


**Figure 2:** Schematic cross-section of a typical fluidized bed heat treating furnace.

As an example, the design arrived at based on the above for a typical steel wire annealing furnace will result in Zone 1 firing all the time when the furnace is fully loaded, with gas modulating or cycling on/off in subsequent zones, with identical air flows in each zone. For a typical low carbon steel wire reaching an annealing temperature of 710°C in a 730°C fluidized bed, the total heat absorbed by the wire will is calculated to be 446.8 kJ/kg of wire. Of this total heat absorbed, 65.8% of this heat will be absorbed in Zone 1, 25% in Zone 2 and the remaining 9.2% in Zone 3 in a 3 zone furnace. At full load, the furnace will be operating as follows:

| | Zone 1 | Zone 2 | Zone 3 |
|---|---|---|---|
| Gas on Time (%) | 100% | 56.3% | 39.4% |
| Effective Excess air (%) | 5% | 87% | 167% |

**Table 1:** Furnace loading with all zones set to same fluidizing rate, 100% capacity

It should be noted that there is no effective difference whether the gas control system used is modulating or time-proportioning (on/off). Both methods deliver identical results as far as overall fuel consumption is concerned. As can be seen from Table 1, while Zone 1 operates at 5% excess air (by design) at 100% load, Zones 2 and 3 operate at high levels of excess air. As a result, the heat energy supplied by the fuel not only goes to heat the product, it must also provide energy to heat the excess air not used for combustion to the furnace temperature of 730°C. This energy is essentially wasted heat as it is not used for product heating. The situation becomes even worse if the furnace is not operating at a full load. For example, if the furnace described above were to be operated at 50% of maximum load, the resulting gas on times and excess air rates would be as shown in Table 2 below:

| | Zone 1 | Zone 2 | Zone 3 |
|---|---|---|---|
| Gas on Time (%) | 64.8% | 40.8% | 32.8% |
| Excess air (%) | 62.4% | 145% | 205% |

**Table 2:** Furnace loading with all zones set to same fluidizing rate, 50% capacity

As a result, the calculated fuel used per tonne of production increases from 26.9 $m^3$ gas/tonne to 39.2 $m^3$ gas/tonne, an increase of 45%. Clearly, the fluidized bed configured to operate with all zones set to the same fluidizing rate cannot be operated at light loads efficiently.

However, in light of the fact that the fluidizing rate does not significantly influence the heat transfer rate (at least at fluidizing rates beyond 2 x $U_{mf}$) there is an opportunity to alter the set-up of a fluidized bed to improve its thermal performance. For example, if the furnace is designed such that Zone 1 is set up so that it is operating at 6 x $U_{mf}$ at 5% excess air at full load, Zone 2 set to half the air flow of Zone 1 (ie 3 x $U_{mf}$) and Zone 3 set to 1/3 the air flow of Zone 1 (ie 2 x $U_{mf}$ ), then all zones would be providing similar heat transfer rates, but Zones 2 and 3 would have much lower air flow rates than Zone 1. The resulting furnace operating conditions at 100% and 50% capacity are summarized in Tables 3 and 4 below:

| | Zone 1 | Zone 2 | Zone 3 |
|---|---|---|---|
| Gas on Time (%) | 100% | 82.9% | 59.0% |
| Excess air (%) | 5% | 27% | 78% |

**Table 3:** Furnace loading with Zone 1 set to 6 x $U_{mf}$, Zone 2 set to 3 x $U_{mf}$ and Zone 3 set to 2 x $U_{mf}$, 100% load.

| | Zone 1 | Zone 2 | Zone 3 |
|---|---|---|---|
| Gas on Time (%) | 64.8% | 56.2% | 42.1% |
| Excess air (%) | 62.4% | 87.3% | 137% |

**Table 4:** Furnace loading with Zone 1 set to 6 x $U_{mf}$, Zone 2 set to 3 x $U_{mf}$ and Zone 3 set to 2 x $U_{mf}$, 50% load.

Comparison of Tables 3 and 4 to Tables 1 and 2 clearly shows that staging the air flow in the zones substantially reduces the amount of excess air to be heated, hence increasing the thermal efficiency. The resulting gas usage per tonne of production for the staged air case is now 22.2 $m^3$ gas/tonne at 100% capacity and 29.7 $m^3$ gas/tonne at 50% capacity, an improvement of 17.6% and 24.0% respectively over the "all zones the same" case above.

Even further improvements in energy efficiency can be achieved if all zones are allowed to modulate both gas and air within the same 2 x $U_{mf}$ and 6 x $U_{mf}$ range suggested above. The modulating system would be set to provide 5 – 10% excess air through the modulating range. If a zone requires less heat than provided at 2 x $U_{mf}$ and 5% excess air, the air flow would be fixed at 2 x $U_{mf}$ and the zone would then either modulate gas only or go to gas on-off control to prevent defluidization and zone overheat. The resulting fuel used per tonne of production would be 21.7 $m^3$ gas/tonne at 100% production and 24.3 $m^3$ gas/tonne at 50% production, an improvement of 19% and 38% respectively over the "all zones the same" case. Figure 3 shows the fuel consumption per tonne of wire versus the production rate for all three control schemes discussed above. Although all control schemes result in increased fuel usage as furnace loading is reduced, clearly a considerable amount of fuel can be saved under all operating conditions by using either staged zone control or modulating control.

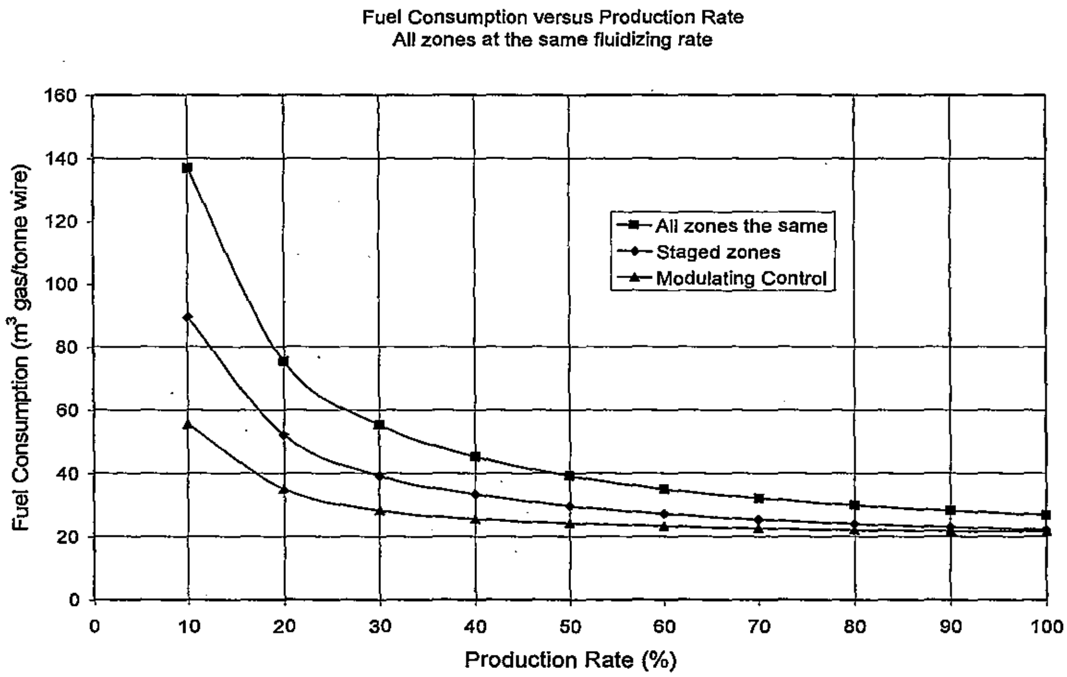


**Figure 3:** Fuel usage versus furnace loading using three different control schemes

## IMPLEMENTATION

New furnaces can be designed from the start to operate in either of the two operating modes. Staged zone control can easily be achieved with little or no change to the control system design, while modulating control would require relatively simple and inexpensive changes to the fuel and air controls. Existing furnaces can also be easily modified. A furnace that currently operates using on/off gas controls can be modified simply by changing the sand grit size such that Zone 1 operates at around 6 x $U_{mf}$, then adjusting Zones 2 and 3 to achieve the desired fluidizing rates. The furnace stacks may have to be modified to prevent sand carryout at the higher fluidizing rate/smaller sand size, though it is expected that the stacks in most furnaces would be adequate.

Modifying existing furnaces to operate using modulating controls would be somewhat more involved, as the control panel and fuel/air flow control systems would require modifications. However, greater fuel savings would be achieved. Whether the change would be feasible would depend on the specific application and furnace design.

In terms of potential savings, consider a typical furnace designed to operate for 6000 hours per year at a maximum capacity of 4 tonnes/hour (24,000 tonnes/year). Recognizing that most furnaces are somewhat overdesigned, and that it is nearly impossible for a producer to maintain a product mix that maximizes throughput at all times, it will be assumed that actual output is 20,000 tonnes/year, and that the typical furnace loading is 80% of maximum. Based on this, Table 5 summarizes fuel use and cost, using a base fuel price of $0.40 US/m$^3$, current typical gas costs in the Canadian market. In addition, greenhouse gas emission reductions ($CO_2$) are listed.

| Control Scheme: | All zones the same | Staged Zones | Modulating Control |
|---|---|---|---|
| Annual fuel use: (m$^3$) | 600,000 | 482,000 | 443,600 |
| Annual fuel cost: (US$) | $240,000 | $192,800 | $177,440 |
| Annual Reduction in $CO_2$ emissions | 0 | 212,400 kg/yr | 281,500 kg/yr |
| Annual Savings: (over 'All Zones the Same" control) (US$) | $0 | $47,200 | $62,560 |

**Table 5:** Potential fuel savings for 20,000 tonne/year plant, 80% average furnace loading

As can be seen, substantial reductions in fuel use, greenhouse emissions and cost can be achieved, even in a plant which operates its furnace(s) near capacity. Plants that use less furnace capacity would save proportionally more fuel. It is expected that payback for any costs incurred in changing an existing furnace's control scheme could be recouped in a year or less for many plants.

## CONCLUSIONS

Recent research on heat transfer rates to wires and strips in a fluidized bed has shown that modulating control or staged control of fluidized beds used for heat treating wire is feasible. The benefits of using these control schemes include a substantial reduction in fuel use, and a corresponding reduction in harmful emissions. New furnaces can be built to operate using these control scheme at minimal cost, and existing furnaces can be easily modified in most cases.


## ACKNOWLEDGEMENTS

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## DEDICATION

This article is dedicated to the memory of Philip Cowie (1963 – 2006), a good friend and enthusiastic supporter of the ongoing development of the fluidized bed and the wire industry.

## REFERENCES


1 Crowle, W.E.:"Annealing Carbon Steel Wire in a Fluidized Bed" Wire Industry V. 52 No. 621, 1985, pp 548-550

2 Saxena, S.C.: "Heat Transfer between Immersed Surfaces and Gas-Fluidized Beds," Advances in Heat Transfer V.19, 1989, pp 97-190

3 Friedman, J., Koundakjian, P., Naylor, D., Rosero, D.: "Heat Transfer to Small Cylinders Immersed in a Fluidized Bed", Journal of Heat Transfer V. 128, 2006, pp 984-989

4 Rosero, D.:"Heat Transfer to Small Cylinders and Flat Strips Immersed in a Fluidized Bed", MASc thesis, Ryerson University, 2006

5 Turns, S.R.:"An Introduction to Combustion, 2nd Ed" McGraw-Hill, 2000

6 North American Manufacturing Co.:"North American Combustion Handbook Volume 1, 3rd Ed.", North American Manufacturing Co., 1986