Modelling of high speed gas quenching

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Abstract

Gas quenching has been used in vacuum furnaces for many years and its characteristics for bulk quenching of components are well known. More recently the use of gas quenching applied to single or small groups of components that were heated in either vacuum or conventional atmosphere furnaces has been proposed. Gas quenching may be seen as meeting the needs of modern “batches-of-one” processing for “just-in-time” manufacturing. It is clean, non-toxic and leaves no residues to be removed after processing.

If this process is to be possible then heat extraction rates equivalent to those obtained from a medium quench oil must be achieved uniformly at the surface of real components. There are several strategies for meeting this aim: first, conventional high pressure quenching; second, moderate velocity quenching utilising a high heat transfer coefficient gas such as helium; and third, high velocity quenching utilising a gas with lower thermal efficiency. The implementation cost for the first strategy is high as is the running cost of the second unless high cost gas recycling equipment is considered. In the third, overall costs can be minimised by using a low cost gas such as nitrogen without the need to recycle.

It is this third strategy which is the subject of this paper. Computational Fluid Dynamics (CFD) was used to determine if indeed the process could achieve the required results and then to optimise the process parameters off-line. Implementation of a feasible process will then be carried out in the field.
1 Introduction

Gas quenching employing, usually, nitrogen, argon and helium at pressures of up to 60 bar has been used in vacuum furnaces for several years and its characteristics for bulk quenching of components are well known [1]. More recently the use of gas quenching applied to single or single layers of components that were heated in either vacuum or conventional atmosphere furnaces has been proposed [2]. To eliminate the need to cool the furnace structure as well as the components these techniques often involve the transfer of the component to be quenched to a specially designed cold chamber [3]. Gas quenching of single components in this way may be seen as meeting the needs of modern “batches-of-one” processing for “just-in-time” manufacturing. Unlike liquid-based quenchants, gas quenching is clean, non-toxic and leaves no residues to be removed after processing. It has been suggested (Figure 1) that, when considering single components rather than large batches, much higher quenching rates can be achieved for the same gas and quenching pressure.

![Figure 1: A comparison of bulk load and single component gas quenching][2]

In order to meet the criteria for uniform gas quenching the velocity of the gas at the surface should be as high as possible and as perpendicular to that surface as possible to maximise heat transfer [4]. The velocity and angle of incidence to the surface must be as uniform as possible as the heat transfer coefficient is dependent on both (Figure 2). It has been suggested, therefore, that to maximise this effect and minimise the interaction factor between the streams, the distance between the
orifice and the surface should be as large as possible consistent with loss of velocity with distance.

![Diagram](image)

Figure 2: Relative heat transfer coefficient as a function of impact angle of the cooling gas [5].

A second requirement for uniform quenching is that it is necessary for the quenchant to reach the surface of the component uniformly. It is obviously not possible for the gas to arrive uniformly perpendicular to the surface as it is also necessary for the gas to leave the surface uniformly. Thus discrete regions of arrival and departure must exist. Ideally these regions would be infinitely small but practical considerations necessitate that they be as large as possible consistent with effectively uniform heat extraction.

A third factor is the interaction of the individual gas streams. It has been shown that, for constant mass flow per incident gas stream, and a ratio of stream width to distance between the orifice and the surface of four, the heat transfer coefficient reaches a maximum when the distance between the streams is three times the width of the stream [6]. The turbulent vortices formed at the edges of the arriving gas stream are known to have a significant effect on the heat transfer. The form and size of these vortices is difficult to predict due to the complex nature of the interaction between the streams.

It has been suggested that the optimum values for the nozzle array to meet the criteria above is when the distance between the nozzle array and the surface to be cooled is between two and eight time the diameter of the nozzle and when the distance between the centre-lines of the nozzles is between four and eight times the diameter of the nozzle [7].
2 Modelling

The modelling work was carried out using the Fluent v5.0 computational fluid dynamics software package. For this initial screening only two dimensions were modelled to speed up the process. The model consisted of an array of gas nozzles 12.7 mm (0.5 inches) in diameter perpendicular to the hot surface. The distance between the nozzles and the surface (a) and the distance between nozzles themselves (b) was varied for a range of imposed gas velocities (v) at the exit from the nozzle. A typical velocity profile derived from the model is shown in Figure 3a. A closer view of the velocities at the surface (Figure 3b) shows that the flow over the majority of the surface is far from the optimal perpendicular and is in fact parallel to it, reducing the maximum heat extraction rate (Figure 4).

![Figure 3a: A typical velocity profile for v=100 m/s, a=50.8 mm (2 inches) and b=88.9 mm (3.5 inches).](image)

The heat transfer coefficient for the hot surface was calculated as a function of the distance from the centre-line of the nozzle. A typical result is shown in Figure 5. As may have been expected from Figure 3b, the heat transfer coefficient is at a maximum at a position directly below the outside edge of the nozzle where the vortices form, falling off as the flow becomes more parallel to the surface.
The surface heat transfer profile for each set of conditions was characterised using three points on the curve: the maximum cooling rate achieved (typically between the centre-line of the nozzle and its edge), the minimum cooling rate achieved (typically at the point half way between the nozzles), and the midpoint value, half way between the minimum and the maximum. These values were plotted as a function of distance between nozzles (b) in Figures 6 to 8 and the distance between the nozzle and the surface (a) in Figures 9 to 11 for a gas velocity of 100 m/s.
Figure 6: The variation of surface heat transfer coefficient with the distance between nozzles (b) for $v=100 \text{ m/s}$ and $d=101.6$ mm (4 inches)

Figure 7: The variation of surface heat transfer coefficient with the distance between nozzles (b) for $v=100 \text{ m/s}$ and $d=50.8$ mm (2 inches)

Figure 8: The variation of surface heat transfer coefficient with the distance between nozzles (b) for $v=100 \text{ m/s}$ and $d=25.4$ mm (1 inch)

Figure 9: The variation of surface heat transfer coefficient with the distance between the surface and the nozzles (a) for $v=100 \text{ m/s}$ and $b=88.9$ mm (3.5 inches)

Figures 6 to 8 indicate that there is probably a value for the distance between nozzles (b) at which the heat transfer coefficient is a maximum. It is evident that the value of b at which this maximum occurs is different for different values of $d$, the distance from the surface, and probably lies in the range $b=4$ times the nozzle diameter (d) to $b=8$ times d. This result confirms previous work by others.\[\text{[7]}\]
Figure 10: The variation of surface heat transfer coefficient with the distance between the surface and the nozzles (a) for \( v = 100 \text{ m/s} \) and \( b = 38.1 \text{ mm} \) (1.5 inches)

Figure 11: The variation of surface heat transfer coefficient with the distance between the surface and the nozzles (a) for \( v = 100 \text{ m/s} \) and \( b = 12.7 \text{ mm} \) (0.5 inches)

Figure 12: The variation of surface heat transfer coefficient with the distance between the surface and the nozzles (a) for \( v = 300 \text{ m/s} \) and \( b = 12.7 \text{ mm} \) (0.5 inches)

Figure 13: The variation of surface heat transfer coefficient with the inverse of the distance between the nozzle and the surface for \( v = 100 \text{ m/s} \).

The data for 50 and 300 m/s gas velocities show very similar trends to the 100 m/s data. The surface heat transfer coefficient as a function of the distance between the nozzle and the surface (for the same conditions as Figure 11 except for an increase in gas velocity to 300 m/s) is shown in Figure 12.

From these data it is obvious that the interaction of the gas streams is complex and that it is not possible to describe the interaction as a simple function. However, plotting all the data on a single graph (Figure 13) indicates that the heat transfer coefficient is inversely proportional to the distance between the nozzle and the surface. While the distance between nozzles has an increasing effect at larger values of a, its effect at small values appears to be minimal up to at least three times the nozzle diameter.
While several workers have previously reported the maxima in maximum heat transfer rates above the trend line in Figure 13 which occur in the region of $a=8*d \text{ and } b=8*d^{[6\,7]}$. The rapid increase in heat transfer rate at very small separations ($a<d$) have not been reported. The high maximum heat transfer rate in this region is also associated with a high mid-point and minimum heat transfer rates. This is particularly important if even quenching is to be achieved.

3 Discussion

Figure 12 indicates that quench rates equivalent to conventional oil quenching (Grossmann number $H=0.8$) can be achieved with nitrogen alone without the need for a high pressure quenching environment. With additions of hydrogen, which gives three times the cooling rate of nitrogen, it may be expected that quench rates equivalent to that of water could be achieved. Hydrogen additions would have the additional advantage of keeping the component bright during the quenching process but at higher cost than nitrogen alone.

The small distances between the nozzle and the surface needed for maximum cooling has some practical implications. As the distance decreases below the diameter of the nozzle the supply pressure required to drive the gas to the required velocity will increase. To generate such pressures using blowers in the conventional manner would be impractical and expensive in terms of both capital and running costs. However, if nitrogen (or nitrogen/hydrogen mixtures) from a compressed or liquid supply were employed the driving force is effectively free, the only cost being that of the gas itself. Even this is not a total loss as the cold wall quenching chamber could be run at a small excess pressure, say 10,000 Pa (1.45 psi), and the quenching gas used as the whole or part of the heat treatment protective atmosphere.

As a result of the high pressures used it should be possible to eliminate the need for a product support during quenching. The effect of the product’s weight will be small compared to the applied force of the gas and the product would float within the nozzle field. Small inconsistencies would be introduced into the flow field in a practical device and would lead to oscillation or rotation of the component producing more even quenching. The high velocities used will lead to high noise levels in the vicinity of the quench. However, it should be possible to minimise this effect by proper use of sound insulation around the cold wall quenching chamber.

Because the cooling rate is directly related to the gas velocity and the velocity to the supply pressure it is obviously simple to control the cooling rate. Not only is it possible to achieve a controllable rate but that rate can be varied through the quench cycle to produce any cooling profile within the limits of the maximum rate available. Thus austempering and marquenching are easy to achieve.
Let us take as an example a typical automotive gear 150 mm diameter with a 20 mm face and a 20 mm bore (Figure 14). The total surface area is approximately 0.045 m² and the total mass is approximately 1.35 kg. Assuming a nozzle configuration where the gap between nozzles is three times the nozzle diameter and a gas velocity of 100 m/s is required to achieve $H=0.8$ then the cooling time is approximately 30 seconds. The volume of gas required to quench one gear is 3.9 m³. The pressure required to create the required velocity at the nozzle tip is approximately 100 kPa (1 barg) thus the force being applied to one side of the gear is 5.3 kg, which is well in excess of the weight of the gear.

Figure 14: Schematic of gear quenching.

4 Conclusions

Gas quenching of individual components using nitrogen alone in a non-pressurised environment can achieve oil-like quenching characteristics. In order to achieve these rates the gas delivery nozzles must be at a distance from the component that is less than the diameter of the nozzle. For larger distances between the nozzle and the surface, the heat transfer coefficient is at a maximum for distances between the nozzles in the nozzle field of between four and eight times the diameter of the nozzles.
42 Surface Treatment

References


