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Flow Control in Gas Pressure Quenching for Reducing Distortion Potential

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High pressure gas quenching is an established heat treatment process that has some obvious advantages compared to the use of liquid quenchants: a low impact on the environment, the possibility of a more direct control of the quenching results and reduced distortion.

In this paper, concepts for the optimization of the high pressure gas quenching process of parts that are arranged in a load are presented. With the aid of numerical simulation, using different detailed levels of the process and experimental investigations in a model chamber as well as in industrial gas quenching facilities, guidelines are developed for a more uniform quenching. Here, two aspects of the process are covered: On one hand, the arrangement of the parts in the load and the interaction with the upstream flow profile and the flow distribution is analyzed. On the other hand, the possibilities of how to effectively control the local flow are shown e.g. by mounting nozzle systems inside the load for a locally focused and increased heat transfer from the parts. Using these nozzles, parts can also be quenched asymmetrically for compensation of their distortion potential. A heat transfer measurement technique for verification of the numerical results is introduced briefly.

Keywords: heat treatment, gas quenching, high pressure quenching, flow optimization, reducing distortion

0 INTRODUCTION

The control of the heat transfer process from distinct surfaces of work pieces in the quenching process gives the possibility to directly modify the development of the distortion potential release that has been accumulated in previous production processes or is based on material characteristics and geometrical properties. Here, opposite to the use of liquid media, gases have the advantage since within common temperature ranges, no phase transition occurs and a steady relation between the heat transfer and the surface temperature exists. Additionally, gas quenching leaves the part, the quenching equipment, and the facility free from contaminations and therefore, the process has a low impact on the environment.

Gas quenching is used in the industrial production of parts like shafts, axes, cogwheels, rings or bevel gears made of high alloyed steels, (like cold- or hot work and high-speed steel) Edenhofer [3] and Preißer [8]. For increased efficiency, the process is usually operated in batch mode: the parts are arranged in a load that is put into the quenching chamber and subsequent to heating and austenitizing, the parts are quenched using inert gases that are pressurized up to 20 bars for higher heat transfer.

In this paper, different principles that control the heat transfer from the parts surface within batch mode high pressure gas quenching are described. Possibilities to directly and indirectly control the local flow structures in the environment of the parts are discussed. Finally, a measurement technique that can determine local heat transfer coefficients is briefly described.

Numerical results were generated using the CFD Code Fluent 6.3. The calculations were made for a model chamber geometry with air at ambient conditions and were verified in this model chamber that is geometrical analog to industrial quenching chambers but operates at ambient conditions. It exhibits acceptable fluid dynamical similarity to real high pressure gas quenching processes Schmidt [8]. Additionally, quenching runs in a double-chamber vacuum furnace were performed.

1 FLOW CONTROL

The modification of the heat transfer distribution on distinct part surfaces is desirable in high pressure gas quenching. The following

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possibilities to control the quenching medium flow in quenching processes are discussed,:

1. Modifying the incoming flow profile by matching the spatial distribution pattern of the parts in the load.
2. Applying fixtures inside the load for local flow modification.
2.1. Blocking local cross sectional areas.
2.2. Locally redirecting the flow inside the load.

As (model-) parts in this investigation, different cylinder geometries are used: long cylinders with a diameter of 40 mm and a length of 600 mm, which represents long shafts or axes and short cylinders with a diameter of 20 mm and a length of 100 mm, which represents bolts or pins.

1.1 Modifying the Incoming Flow Profile by Matching the Spatial Distribution Pattern of the Parts in the Load.

The distribution of the gas flow velocity in the inlet section of the quenching chamber was identified as a key factor Schmidt [10], [11]. It is responsible for the flow structure inside the quenching chamber and thus determines the local flow velocities and finally the heat transfer distribution from the parts. This profile is the result of the interaction between all upstream placed entities, like the global flow guidance, the flow redirection, the heat exchanger, and the fixtures, as well as guide plates that are used for flow modification. The interaction between upstream velocity profiles exhibiting varying homogeneity and different patterns of the parts in the load were analyzed numerically. Therefore, the gas quenching process is investigated in a multi level approach, from the global process level down to the local level. Due to the complexity of industrially used quenching systems, a three layer model (macro-, meso- and micro) that allows the simplification of certain parts of the geometry which leads to faster convergence of the numerical calculations is introduced.

1.1.1 Global Flow Structures Inside the Chamber (Macro-Scale)

To account for different quenching chamber configurations, e.g. the shape of the redirection area and the usage of baffles, the flow structures for various situations were simulated, but replacing the load with a porous body that puts a certain resistance to the flow. As a result, a number of load upstream test profiles were generated. Typically, these profiles exhibit high velocities to the center of the load. Additionally, a profile with high velocities at the side of the load were generated. From these profiles, the standard deviation σ_{Re} of the velocity profile is calculated, representing the gas velocity homogeneity. Therefore, the local Re number is calculated with the local gas velocity and a characteristic dimension for the model chamber. The standard deviation from this local Re number distribution is σ_{Re}.

1.1.2 Heat Transfer Distribution Inside the Load (Meso-Scale)

The test profiles described in 1.1.1 were applied to a cylinder load (600 x 600 x 1000 mm^3) built from maximal 240 long cylinders (Ø = 40 mm, L = 600 mm). Here, three load configurations were tested: a uniform distribution of the parts, a pattern with a dense packing and a pattern with a loose packing in the centre of the chamber. As a characteristic parameter for the quenching homogeneity, the uniformity of the heat transfer distribution from the parts, the standard deviation of the mean heat transfer over the surface of all parts in the load $\sigma_{q,}$ was chosen. A small σ_q corresponds to a homogeneous quenching result. It can be observed that with increasing inhomogeneity of the flow σ_{Re}, the resulting heat transfer inhomogeneity from the parts σ_q increases in a linear pattern (Figure 1). For loads where the cylinders are arranged contrary to the velocity profile, the inhomogeneity is the largest. The heat transfer homogeneity is better for loads with homogeneous packing of the parts. The best results produce loads where the cylinders are arranged according to the upstream profile.

The effect of the upstream profile on the distribution of the heat transfer was verified in a quenching run in a double-chamber vacuum furnace: A two layer load (400 x 400 x 600 mm^3) was set up with 366 cylindrical parts (Ø = 20 mm, L = 100 mm), maximum packing density and a total weight of about 130 kg. The load was austenitized at 850 °C for 2 h in vacuum and then quenched with N_2 at 10 bar pressure.

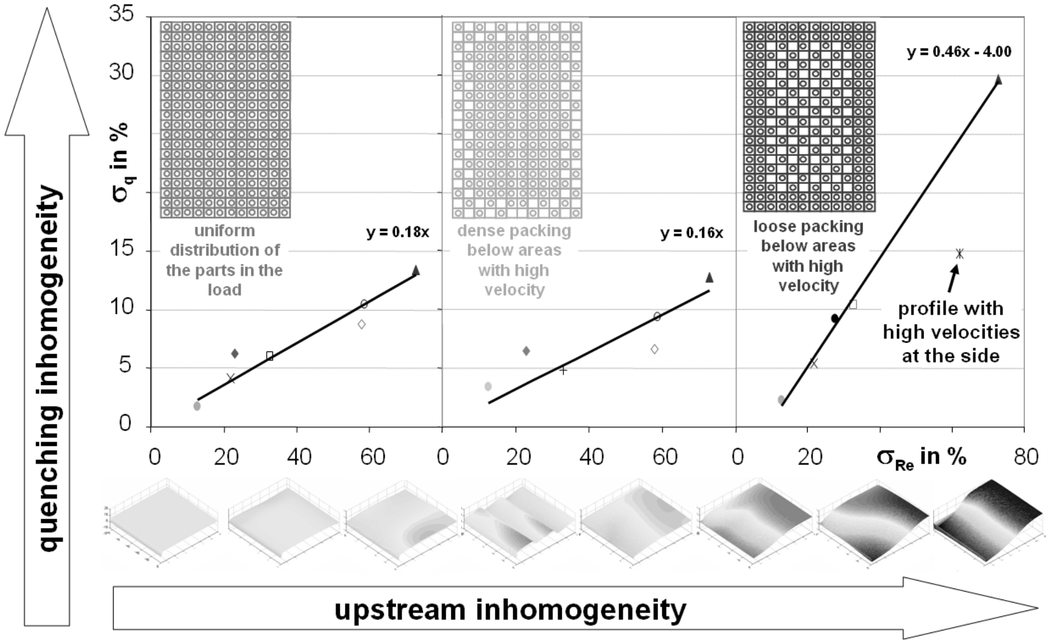


Fig. 1. *Heat transfer homogeneity σ_q depending on standard deviation of the upstream flow σ_{Re} for different load arrangements. Bottom: velocity profile upstream of the load (1/4 cross section). Due to no-slip condition, the uniform profile always exhibits an inhomogeneity, [11]*

With a number of hardness test specimen (made from 20MnCr5 / 1.7147), the response on different upstream velocity profiles is shown. The distribution of the upstream flow velocities is to a certain degree reflected in the distribution of the hardness scattering. In regions with lower gas velocities, the heat transfer from the probes is relatively small and due to the according slow cooling, the resulting hardness is low as well. Probes that are placed below the upstream profiles highest velocity areas are exposed to a larger heat transfer rate, thus the cooling velocity and the corresponding hardness values are high.

1.1.3 Considering Parts Geometry and Loading Equipment (Micro-Scale)

Because of its distinct cross sectional blocking, the effect of the loading equipment and the local flow structures has to be considered in detail. For the analyses of that effect a full simulation was performed for a single cylinder out of the whole load in focus (stepped cylinder, see figure 2, left). Its geometry was derived from real axes and shafts, additionally, the grid holding the cylinder in position is displayed. The numerical results show, that the grid is responsible for a major pressure drop. The additional blocking due to the grid and other load equipment presses part of the quenching media into the gap at the chamber wall – especially at the outer areas of the load. The overall pressure drop results from the flow vertex formation after passing the grid rod and the associated blocking of the local cross sectional area. Consequently, it might be advantageous to set an inhomogeneous upstream profile with higher velocities to the middle of the load.

1.2 Applying Fixtures Inside the Load for Local Flow Modification

For complex parts that are sensitive to distortion or parts with different hardness specifications on functional surfaces it might be necessary, to locally adjust the quenching intensity. Therefore, it may be advantageous, to redirect the quenching gas through appropriate fixtures in the quenching chamber. This enables to locally focus the gas flow and thus control the heat transfer from distinguished surfaces of the parts, which can also be quenched asymmetrically for compensation of their distortion potential. For the development of suitable fixtures, the following boundary conditions and constraints need to be considered:

- It is desirable to achieve a homogeneous heat transfer among the surface.
- The flow resistance of the system should be minimized to set a maximal total volume flow rate.
- The amount of thermal energy that is inserted into the system applying the nozzles should be as small as possible to reduce the heating of the quenching medium itself.
- The system must be applicable into existing quenching chambers without any greater efforts. Alternatively, commercial chamber concepts should be easily adapted to fit with the developed system.

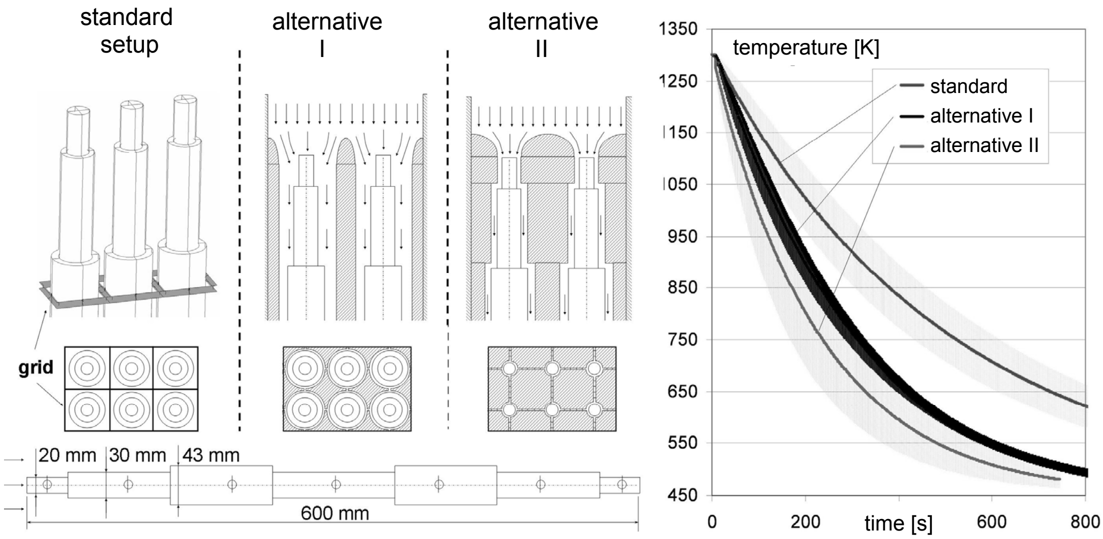
The possibility of installing a cooling system into the fixtures, which may cover the function of the heat exchanger or could provide a higher temperature gradient between part and quenching medium involves some major difficulties and risks because of the requested fragile construction of the fixtures. Consequently, only fixtures without internal cooling are taken into account.

1.2.1 Blocking the Local Cross Sectional Area to Increase the Local Flow Velocity

The flow pattern around the parts can be modified by an adapted cross sectional blocking inside the load to promote higher flow velocities and therefore higher heat transfer rates.

In Fig. 2a the standard setup of shafts in a load frame is shown. For alternative I, blocking bodies which limit the flow in a channel around the shaft were inserted. For alternative II, the blocking bodies were adapted to the shape of the shaft in such a way that the gap has a constant cross sectional area. The results of a quenching simulation with N_2 at 10 bars are shown in Fig. 2b.

It can be seen that the average quenching intensity increases from the standard setup to the alternatives I and II. Furthermore, the scattering of the cooling curves for the standard setup and alternative II is quite high. Alternative I exhibits a very homogeneous cooling. In addition, it is easier to perform this option in high pressure gas quenching chambers and the amount of thermal energy that is brought into the process is smaller compared to alternative II.



a) b)

Fig. 2. *a) different possibilities to modify the flow: standard setup and alternatives, b) simulated average cooling curve ± standard deviation from 7 points on the axis of the shaft from 20MnCr5, quenching with* N_2 *at 10 bars, 10 m/s at 450 K, calculation without phase transformation*

1.2.2 Locally Redirecting the Flow Inside the load

A more advanced method of releasing the heat transfer from the parts, is the use of a conventional quenching in a adaptable nozzle field ("single point jet quenching") that enables a more controlled and a much higher local heat transfer compared to batch mode high pressure gas quenching of parts in a load setup Wünning 14], Edenhofer [3], Gondesen [7] and Schüttenberg [12]. In industrial production, single parts are placed inside the nozzle field and then quenched using high velocity gas jets that are directed normally at the work piece surface to generate a maximum heat transfer. The nozzle system is adaptable, single segments may be controlled individually and are adapted to the specific parts geometry. Hence, besides a symmetrical and uniform heat transfer distribution Bergmann [5], a locally focused quenching of distinct surfaces of the parts is possible Brzoza [1]. A disadvantage of the nozzle systems is that a batch mode quenching of multiple parts is not feasible - single parts are treated individually; a larger lot size is only possibly to a limited extent.

Installing a nozzle system inside the quenching load would combine the advantages of batch mode quenching and single point jet quenching. In a suitable setup, the quenching medium flow is directed from its global circulation in the quenching chamber and into the nozzle system that is integrated inside the load. Here, differently from conventional single point jet quenching, the area around the parts is restricted by the quenching chamber geometry and the number of parts to be quenched. Hence, the space for the quenching medium to be removed from the process is limited and there is a stronger interaction in-between the jets from each nozzle. Consequently, to avoid an unequal distribution of the flow in the nozzles, the system has to be designed carefully.

In this paper, a nozzle system as shown in Fig. 3 is introduced. Subsequent to the heating of the parts in the furnace, a nozzle frame is descended from above the load e.g. supported from guide slots. That nozzle frame is blocking the bulk flow in the chamber and is redirecting it into the openings around the parts. Here, along the parts length, the nozzle holes which are directing the quenching gas normally to the parts surface for an increased heat transfer are situated.

The simulation results of the nozzle system using simple nozzle holes are shown in Fig. 4a. It can be seen that due to the limited area, the flow rate in the annular gap gradually increases as it passes each nozzle row, resulting in an increasing mean velocity in the gap. The resulting global flow generates an increasing deflecting effect on the jets from the nozzle - the efficiency of the nozzles is sequentially decreased.

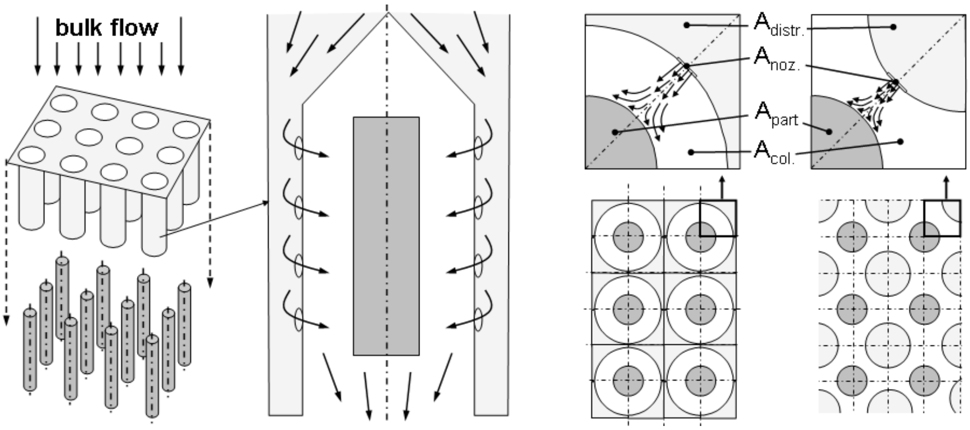


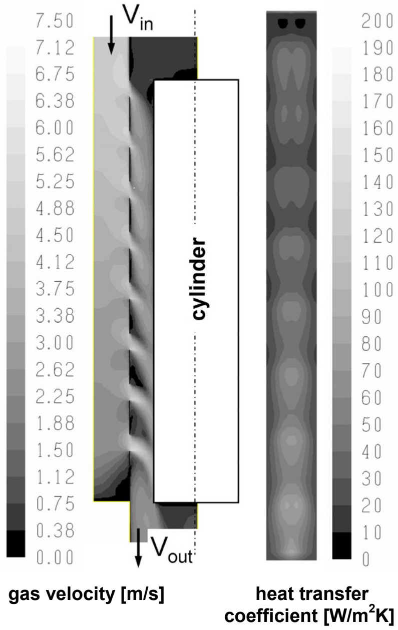
Fig. 3. *Left: applying a nozzle system into the quenching chamber (schematic), right: different possibilities for splitting the cross sectional area into the distributor and the collector (90° symmetry: four nozzle rows on the circumference of each cylinder).*

As a consequence, a modified version is developed, attaching pipes to the holes in the same configuration (Fig. 4b) and the ratio of the cross sectional areas of the distributor and collector is slightly changed to provide a sufficient distance from the nozzle pipe exit to the cylinder surface. This configuration has two effects. Firstly, a more straight guidance of the quenching gas onto the cylinder surface is achieved and secondly, in the empty area around the nozzle pipes, additional space is available to remove the gas.

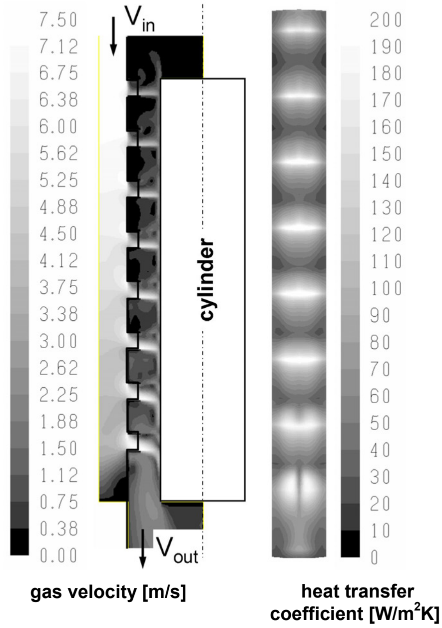
2 DEVELOPMENT OF A HEAT TRANSFER MEASUREMENT TECHNIQUE

For verification of the numerical results, a measurement technique for determining the local heat transfer on the surface of (model-) parts is presented. Here, a commercially available glue-on CTA probe will be used. It is build up as follows: a 0.9 x 0.1 mm nickel sensor is deposited on a 50 µm foil and is carrying a 0.5 µm quartz coating. It is connected via gold-plated lead areas with the constant temperature anemometer (CTA) Dantec [6]. According to Bruun [2], the foil is glued directly onto the substrate in the points of interest, the sensor is operated at constant temperature, balanced from a wheatstone bridge. The heat transfer from the sensor to the fluid can now be determined by measuring the energy that is required for keeping the sensor at a constant temperature. Due to large conductive energy losses from the sensor into the substrate (and into the thermoplastic resin film), the sensibility is reduced and only a small measuring range is available.

The calibration of the sensor was done using the well known relationship between the heat transfer in an impinging jet and the radius of the substrate [13]. The glue on film probe was attached to an adjustable substrate, the velocity of the impinging jet was set to $7\cdot10^3 < Re < 2.3\cdot10^4$, the substrate was moved perpendicular to the jets axis and the resulting voltage were measured (Fig. 5). As can be seen, the calibration curve for the different parameters in use (h* = h/d) fit very well. Additionally, it is possible to find a relation for varying temperatures of the impinging jet.



a)



b)

Fig. 4. *Simulation of the flow structures (contours of velocity magnitude on a symmetry plane) and heat transfer (1/6 view of the cylinder side face) in different nozzle systems, a) preliminary version with nozzle holes, b) modified version with nozzle pipes in the same configuration, 60° symmetry (6 nozzle rows on the circumference of each cylinder), quenching gas is air at 1 bar, mass flow: 3.36 g/s each cylinder*

An important result from several calibration runs is that the substrate and the realization of the glue bond with the thermoplastic resin between the substrate and the sensor foil have a major effect on the measured values from the anemometer. Consequently, the calibration of the glue on HTC probe must be performed with these parameters kept constant. For the determination of the heat transfer from a probe with varying shape, a new calibration method needs to be developed because the results from the impinging jet cannot be translated to that situation.

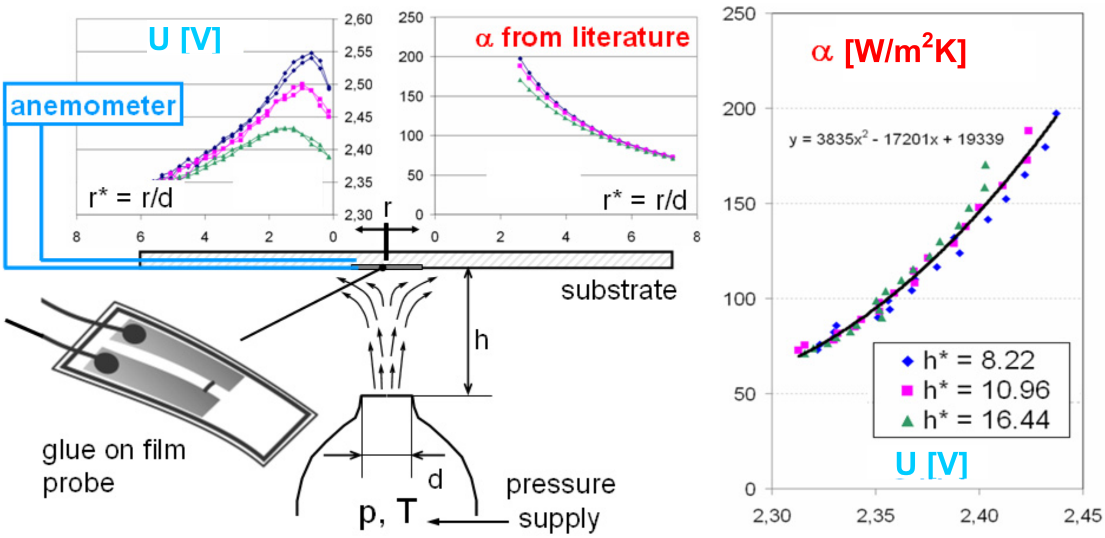


Fig. 5. *Determination of a calibration curve for the HTC glue on film measurement technique, a) calibration setup using an impinging jet, b)resulting calibration curve between the heat transfer coefficient and the anemometer voltage, literature data for the heat transfer coefficient from [13]*

3 CONCLUSION

In this paper, the possibilities to directly and indirectly control the local heat transfer from parts in gas quenching are discussed. With the aid of flow measurements in a model chamber and numerical flow analyses on different detailed levels, the guidelines of how to modify the upstream flow profile and match the pattern of the parts inside the load for a homogeneous quenching are given: Oblong parts, arranged in the main flow direction have to be arranged a) in the case of a homogeneous upstream profile, in a homogeneous pattern and b) for an inhomogeneous upstream profiles with a dense packing below the areas with the highest velocities.

The heat transfer can locally be controlled by applying fixtures into the load. Numerical studies of two different fixtures concepts were presented: Blocking bodies which limit the flow around the cylinder thus providing a higher local velocity, were inserted into the load. The blocking to a tube-like channel around the part gives the best results, has an increased heat transfer and exhibits a very homogeneous cooling.

A more advanced possibility is to apply a nozzle system into the load that locally redirects the quenching medium normal to the surface of the parts for an increased heat transfer. Here, two options were numerically investigated: simple holes in the nozzle frame resulting in a disadvantageous removal of the quenching gas and the same configuration with pipes attached to the holes. Here, the flow is guided more directly onto the cylinder surface and more space for gas removal is available.

For validation of the numerical results, a technique for measuring the local heat transfer coefficient on parts has been briefly introduced. Calibration tests have shown that the substrate and the realization of the glue bond between the substrate and the sensor foil have a major effect. Consequently, the calibration must be performed with identical parameters. For different shaped probes, a new calibration method needs to be developed.

4 ACKNOWLEDGEMENT

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