**A Revolution in Magnet Wire Production – the All New Mozart Zero.**

With a long history as the innovation leader of the magnet wire industry MAG once again changed the rules of enamelling wire. With a revolutionary energy recovery system the new MAG Mozart Zero’s oven uses zero energy for heating the process air – saving more than half of the machine’s total energy demand.

For a very long time now energetic resources seemed to be pretty much inexhaustible. Energy was widely available and rather cheap. Thus there was, perhaps understandably, very little interest in energy saving methods.

Times are changing

However, this has changed drastically. During the last decades and even more so in recent years we had to deal with an alarming shortage of our energy resources. This resulted in a situation where everything from oil to electric energy becoming automatically more and more expensive. This unstoppable development is, of course, a major issue for the magnet wire industry, with its energy intensive production processes.

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The future in mind

And even though electrical energy is already one of the biggest parts of the total production costs now, its share will increase dramatically over the next years. Making energy consumption one of the most critical points when choosing a new enamelling machine. Which is why believe the MAG’s Mozart Zero is going to revolutionise magnet wire production.
The Serious Idea Behind the Incredible Mozart Zero

by Dr.techn. Klaus Czuputa

MOTIVATION

During the last years, the costs of electric energy have grown dramatically. Fig. 1 exemplarily illustrates the price trend of industrial electricity in Germany for the period 2000 to 2008 showing a doubling of the electricity tariff within eight years only. Many countries all over the world complain about much greater increases in prices.

ENERGY SOURCES FOR HEATING

For wire coating, the consecutively applied enamel films need to be dried and cured. The drying of the films is based on the evaporation of the enamel solvents into the recirculating process air, while the curing process is governed by chemical reactions inside the films leading to cross-linking of polymers. During the enamelling process, the metal wire is compulsorily warmed up, absorbing a lot of thermal energy due to its high heat capacity. In order to keep these processes running, a sufficiently high temperature level is required. This is provided by the process air heated in the oven system. As depicted in Fig. 3, two different machine components provide heat sources used for the heating of air in the oven system – the electric heaters and the catalyst.

Fig. 1: Trend of german electricity rates incl. taxes.

For the industry this leads to significantly higher production costs – also for magnet wire production. As shown in Fig. 2, more than half of the total electric power supply for MAG's established horizontal machine is consumed by the electric heating of the process air.

Fig. 2: Electric power supply for conventional type.

However, it is easy to reconstruct that, during production, electric heating may quite simply be eliminated. These resulting unnecessary costs, borne by the magnet wire producers now, can be saved by a significant reduction of energy losses. Hence, the major objective of MAG's competent R&D team was to take radical measures against the machine heat losses leading to a tremendous reduction of the specific energy demand per unit wire mass.

MEASURES FOR SAVING ENERGY

Following possible measures lead to a considerable decrease of energy losses/demand:

- Heat transfer enhancement between the wire/air interface by improved flow conduction in a specifically designed baking tube geometry leads to lower energy demand at same speed.
- Reduction of oven wall heat loss due to an installed multi-layer insulation decreasing the heat transmission across the oven walls.
- Decoupling of thermal bridges of the oven frame to reduce the heat loss from the core zone by thermal conduction.
- Recovery of exhaust energy into the oven system via highly efficient heat transfer units.
- Efficiency enhancement of the heat exchanger prior to the heating zone due to improved flow conduction and optimized heat transfer area.
- Prevention of wire heat loss by means of thermal insulation of contact zones between the wire and the fibre airspace.
- Regulation of wire temperature based on fully-automatic cooling avoiding unnecessary wire heat losses under controlled conditions.

As shown in Fig. 5, for the given conditions, in total potential savings of up to 28 kW may be achieved through the combination of the technologies listed.

Fig. 3: Electric heaters and catalyst inside the oven.

The heating units are made up of electric coils transforming electric power into heat energy in order to increase the air temperature to a required level. An additional heat input is provided by the catalyst intended for the main part of chemical conversion of the enamel solvents. During the thermal oxidation in the catalyst, the hydrocarbons contained in the solvent vapour mixture react and combine with oxygen, and finally are transformed into water vapour and carbon dioxide. Since the solvent conversion is based on exothermic chemical reactions, a high quantity of heat is released into the system. If high catalytic efficiency is ensured, the amount of produced heat basically depends on the input rate of the enamel solvents and the mean calorific value of the solvent mixture.

BASIC CONCEPT OF ZERO ENERGY OVEN

Fig. 4 depicts the ideal energy balance of a horizontal single oven based on measurements with MAG's highly equipped Mozart test machine during the production of a 0.5 mm wire at 700°C curing zone temperature.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric power supply (oven system)</td>
<td>22.7</td>
</tr>
<tr>
<td>Chemical conversion of solvent vapour</td>
<td>19.1</td>
</tr>
<tr>
<td>Total input</td>
<td>41.8</td>
</tr>
<tr>
<td>Exhaust air</td>
<td>18.6</td>
</tr>
<tr>
<td>Wire cooling outside the oven</td>
<td>16.8</td>
</tr>
<tr>
<td>Total output</td>
<td>41.8</td>
</tr>
</tbody>
</table>


Fig. 4: Energy balance of horizontal test machine.

54% of 42 kW total power input is generated by the electric heaters, while 46% is provided by the chemical conversion of the solvents. At steady state conditions, the required heat input to keep the oven temperature level constant is equal to the total amount of heat losses of the system at all times. The sum of all heat losses therefore yields also a value of about 42 kW, comprising the heat loss by the exhaust air (45%), the wire heat loss outside the oven (50%), the heat loss across the machine walls (14%) and the energy loss due to drying and curing (1%).

Consequently, during production, electric heating is only requested, whenever the total heat losses exceed the amount of thermal energy released through the solvent conversion. According to Fig. 4 that finally means: if the total oven heat loss of 42 kW may be reduced by more than half down to a value of about 19 kW, external electricity for heating is no longer necessary. This is the basic idea to get a “Zero Energy Oven”. Simple enough in theory - but slightly more complex in practice.

Fig. 5: Energy savings per line according to 0.5 mm wire at vxd=200, and 700°C curing temperature.

The resultant heat loss is consequently much less than the heat quantity provided by the solvent combustion. For this reason, the dream of zero electric energy for heating has come true: MAG’s revolutionary Mozart Zero machine.

FULLY-AUTOMATIC PROCESS

The best way to ensure highest efficiency and stable quality is the complete automation of the machine, giving you full control of all crucial process parameters – also realised in MAG's Mozart Zero machine. The adjustment of the convective flow situation and the control of the air temperature in the drying zone guarantees sufficiently smooth solvent evaporation. An optimum adaptation of the internal enamel film thicknesses facilitates uniform drying, resulting in a lower risk of blistering. The regulation of the baking zone temperature ensures constant conditions for curing. The regulation of the recirculation airflow rate enables the control of the fresh air supply at the oven openings, as well as the heat transfer intensity at the wire/air interface.

Energy efficiency, quality assurance and process reliability require constant operating conditions. With an unvarying cooler fan speed, even the slightest changes in ambient temperatures will have considerable impact on productivity, energy demand and the degree of cure. A human operator will not be able to react appropriately and quick enough to the shifts of operating conditions. Which is why machines that require manual adjustments can never ensure optimized conditions.

This is why MAG has researched and developed a fully automated regulation of the wire temperature, also implemented in MAG’s Mozart Zero. In the process, the speed of the cooler fan is coupled to the wire temperature, which is measured at the oven entry with MAG’s specific measurement system based on a non-contact principle (Fig. 6).

Fig. 6: Wire temperature measurement system from MAG.

As a result, the wire temperature serves as a major control parameter. This ensures constant conditions for enamelling and the lowest energy demand for heating the wire – at all times and completely independent from ambient conditions.

WHY COUNT ON MOZART ZERO?

All in all, MAG’s Mozart Zero machine based on an all-automation process control is the essential key to success in magnet wire production ensuring:

- The highest output of enamelled wire due to wire temperature control and optimized heat transfer in the baking zone.
- The lowest energy demand by far because of lowest oven heat losses and most efficient wire heating.
- The best quality-enamelled wire due to optimum drying and curing conditions.
- Highest process reliability and human safety with the lowest scrap during production.
- Stable conditions for lowest downtimes.
- Simplest handling and failure-free, long-term operation without continuous quality checks.
- Lowest manpower requirements and personnel costs.

Compared to the original machines, with Mozart ZERO, the specific energy demand in units of kWh per kg enamelled wire could be cut in half, and thus has no rival. In contrast to competing machines, MAG’s Mozart ZERO will finance itself via energy savings alone within few years. Therefore, all what you need is Mozart ZERO – nothing less.

Acknowledgements: The competent and successful cooperation with the Institute of Fluid Mechanics and Heat Transfer of Graz University of Technology, starting in 2004, is gratefully acknowledged.
High-Quality Wire Coating in MAG Magnet Wire Machines

by Prof. Dr.-Ing. habil. G. Brenn, ao. Prof. Dr. techn. H. Steiner, Dipl.-Ing. Emil Barić

INTRODUCTION
Modern developments in wire coating for magnet wire production aim at using enamels with even higher concentrations of the polymer in the cresol-solvent solution. The advantages are savings in the expensive solvent and, consequently, in production costs. At the same time, however, the coating quality, i.e., the mechanical and dielectric properties of the coating, needs to be maintained. For these reasons, the performance of the nozzles used for applying the liquid enamel to the wire surface has received increased attention. A new research and development undertaking of MAG, together with the Institute of Fluid Mechanics and Heat Transfer of Graz University of Technology, aims at developing a nozzle concept suitable for use with highly concentrated enamels.

AIMS AND SCOPE
A high performance coating process is characterised by high productivity and process safety, together with high product quality. The high productivity involves high throughputs of wire through the machine and, consequently, through the nozzle. This brings about high velocities of the wires and, as a consequence, high shear stresses at the wire surface as it passes the coating nozzle. The resulting stresses may become very high, and it is an aim of the development undertaken to keep them well below the limit determined by the strength of the wire material. This may be achieved by an optimised inner contour of the coating nozzle, which allows for a high wire throughput at limited resisting forces.

COATING NOZZLES IN MAG MACHINES
The enamel is applied to the wire surface by coating units as shown in Fig. 1. A pump conveys the liquid enamel from the storage tank to the short pipe 5 with the passage 4 at its top, from where it emerges. The wire is pulled through that passage and comes into contact with the enamel. The result is a coarsely coated wire with a very thick layer of enamel covering the whole wire surface.

The wire moves along the dash-dotted line from the passage 4 to the nozzle 6. In that nozzle, the bigger part of the enamel layer is stripped off the wire surface by a narrow opening with circular cross section of a diameter exceeding the wire diameter by twice the intended wet coating thickness. The enamel stripped off flows back against the direction of wire motion and leaves the nozzle housing in the form of a thick jet.

PROPERTIES OF THE NOZZLE FLOW
The motion of the enamel through the coating units of the machine is purely sheared driven. The viscosity of the liquid enamel forces the liquid to follow the motion of the wire surface to which it is contacted. We can say that the wire drags along the liquid enamel due to its viscosity. The condition at the contact surface between wire and liquid causing this effect is called the no-slip condition. Another shear-driven flow field, in a plane geometry, called the Couette flow, is shown in Fig. 2. There the upper part moving at the velocity \( v \) to the right may be the wire. The lower part is the nozzle wall, which stands still and forces the liquid to remain at rest there.

In cases that the flow velocities are not too high and the geometrical shape of the flow field is simple, flows of this kind may be analysed by solving the underlying equations of motion. This may be done even analytically if the viscous flow behaviour of the liquid is not too complicated. Subsequently we show how this can be done.

ANALYSIS OF THE ENAMEL FLOW
The motion of the liquid through coating nozzles like the present ones can be essentially described as a laminar flow through a thin annular converging gap as sketched in Fig. 3. The very small gap width \( h \) relative to the length \( L \) of the nozzle, \( h/L < 1 \), allows for simplifications of the equations of motion, generally subsumed as the lubrication theory:

Since the gap is so narrow, the liquid mass entrapped in the nozzle at any time is always small, so that its inertia may be neglected in the calculation. Yet, since variations of the flow velocities in the direction of the gap width are much larger than those along the wire, stresses in the transverse direction may be neglected against those in the axial direction, \( \tau_{xx} \gg \tau_{zz} \).

Also, velocities in the direction of small extensions of a flow field are typically much smaller than those in directions of large extensions, \( v \propto u \). This enables another neglect in the momentum equations.

The fluid was treated as Newtonian with a dynamic viscosity \( \mu = 0.1 \text{Pa}s \). A relatively large region with reversed flow (= region above the dashed line) extends from the entrance of the nozzle deeply downstream. This corresponds to the ejection of a part of the fluid towards the nozzle entrance, which is seen in the real device. Very close to the nozzle exit the axial velocity turns entirely positive, and the liquid exit velocity partly even exceeds the speed of the wire, \( u > U \).

STRESSSES AND FORCES
The axial variations of the non-dimensional pressure and wall shear stress acting on the moving wire as obtained for different nozzle angles \( \Theta \) are shown in Fig. 5. A positive (adverse) pressure gradient is seen for the largest part of the nozzle, which produces the reversed flow seen in Fig. 4. Very close to the exit the pressure drops abruptly to the ambient level, the negative (favourable) gradient redirects the motion entirely to the downstream direction. The peak values of the pressure increase for decreasing angles \( \Theta \). The same tendency is also featured by sliding-contact bearings.

The wall shear stress \( \tau_w \) remains negative along a large part of the wire. It essentially determines the resulting drag force on the wire according to

\[
F_d = -2\pi r_l \int_0^{\frac{h}{r_l}} \tau_w \, dz
\]

The negative sign in front of the integral indicates that regions associated with \( \tau_w > 0 \) add to the drag force, while regions with \( \tau_w < 0 \) reduce it. Accordingly, since the wall shear stress \( \tau_w \) generally assumes lower negative levels for smaller nozzle angles \( \Theta \), the resulting drag force increases with decreasing \( \Theta \). The dependence of the non-dimensional drag force on the nozzle angle \( \Theta \) varying in the range \( 0 < \Theta < 20^\circ \) is shown in Fig. 6.

The present analysis based on the lubrication theory can be extended straightforwardly to non-Newtonian fluids, even though the solution of the governing equations becomes more complicated. As such, this concept provides a reliable analytical approach for improving the geometry of the nozzle contour to keep the drag force on the wire within a range tolerable by the strength of the wire material.

Acknowledgement: Financial support of the projects of cooperation between the Institute of Fluid Mechanics and Heat Transfer of Graz University of Technology and MAG from the Austrian Research Promotion Agency (FFG) is gratefully acknowledged.
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