



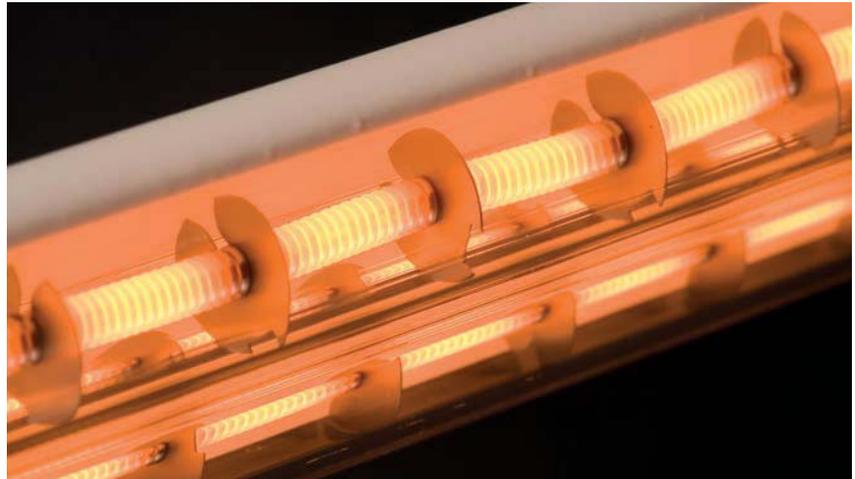
# NUMERICAL ANALYSIS OF IR HEAT TRANSFER PROCESSES

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## INTRODUCTION

**H**eraeus Noblelight is a global business unit of the technology company Heraeus in Hanau, Germany, and counts itself among the market and technology leaders worldwide for special lamps with wavelengths from ultraviolet to infrared for industrial, scientific, and medical applications. With locations in Germany, the United Kingdom, China, and the USA, the segment manufactures lamps for analytical measurement technology and the printing industry, infrared emitters for industrial heating processes, arc and flash lamps, and products for water disinfection and air treatment, as well as sun simulation and photochemistry with a high level of vertical integration.

In order to meet rising expectations of customers and out-perform both predecessors and competitors, Heraeus Noblelight Industrial Processing (HNG-IP) is constantly developing not just standard but also individual infrared emitters and infrared heating systems. An extensive range of products including round or twin tube emitters in linear or in individual 3D geometries with specular or diffuse reflectors is manufactured and incorporated into production cells or modules. In terms of effectiveness, different wavelengths or Infrared (IR) spectral domains – short- or middle-wave range – are suited for different applications.



**FIGURE 1:** Short-wave infrared lamp (source: Heraeus Noblelight)

## CAE REPLACES 'TRIAL AND ERROR'

Complementary to the traditional 'trial and error' methods, Computer-Aided Engineering (CAE) tools based on 3D design (Autodesk), ray tracing (Zemax) and Computational Fluid Dynamics (CFD) (STAR-CCM+®) are now extensively used to achieve a better understanding of IR heat processes like wafer cleaning, paint/lacquer drying or plastics welding and to predict solutions for several technical failures. In all applications, the main technological challenge is to obtain a

well-controlled uniform temperature on the substrate surface. In this respect, the perfect knowledge of radiative heat emitted by the infrared lamps and their behavior under special environmental conditions is mandatory.

The expensive "IR Thermal Process" laboratory verification tests have been augmented or even replaced with more efficient and advanced computational methods. The aim is to investigate the temperature distribution in substrates with complicated structures, to analyze

the robustness and performance of components and assemblies from the thermal perspective as well as the interaction of those with the environment. Furthermore, CAE can accurately predict and visualize the fluid flow pattern within systems with cooling devices like blowers and fans and the influence of temperature gradients or pressure drops or flow's behavior. The main technological challenge is to obtain a well-controlled uniform temperature at the wafer surface, so accurately predicting the radiative heat emitted by the infrared lamps is essential.

In this regard, and using CD-adapco™'s numerical simulation tools, we developed complex three-dimensional models (micro-models) of infrared (IR) lamps accurately representing a lamp portion and including the complete lamp geometry, as well as large size models (macro-models) based on phenomenological assumptions for industrial applications.

**MICRO-MODEL – SIMULATING THE MICROPHYSICS**

The micro-model focuses on the thermal boundary conditions and analyzes the entire physics in the lamp. This model is based on detailed HNG-IP emitter geometries and configurations. A regular or high intensity short wave infrared lamp consists of a tungsten filament in the middle of a quartz bulb. The resistive element is the spiral tungsten coil, operating at 1800-2500 °C and surrounded by a quartz glass envelope, employed by its optical and thermo mechanical properties. Although tungsten has a melting point well above 3200 °C, it would oxidize rapidly and be burned out in an atmosphere containing oxygen. Thus, the quartz envelope needs to be tight to exclude any contact between the tungsten filament and oxygen. Such lamps contain either a vacuum or, more frequently, an inert atmosphere of nitrogen or of a noble gas such as neon or argon. The lamp glass is made of quartz, which has high transmissivity in the infrared range. Thus, most of the radiation emitted is transmitted by the lamp glass. Still, some radiation is absorbed by the glass, which heats up to about 700 °C. Since quartz has high temperature stability, is insensitive to thermal shocks, and has low thermal conductivity and low thermal expansion, the elevation in temperature is not an issue. Since tungsten shows considerable thermal expansion, however, it is difficult to maintain perfect tightening when the lamp is in operation. In practice, the conductor is fitted into the tube by use of a small piece of molybdenum, as indicated in Figure 1. Above about 350 °C,

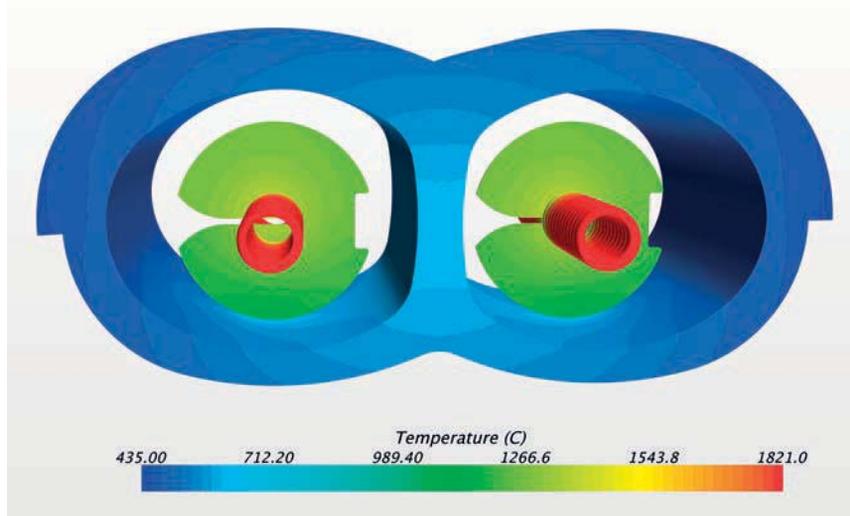


FIGURE 2: Micro-model - Geometrical set-up (source: Heraeus Noblelight / Dr. Lotta Gaab)

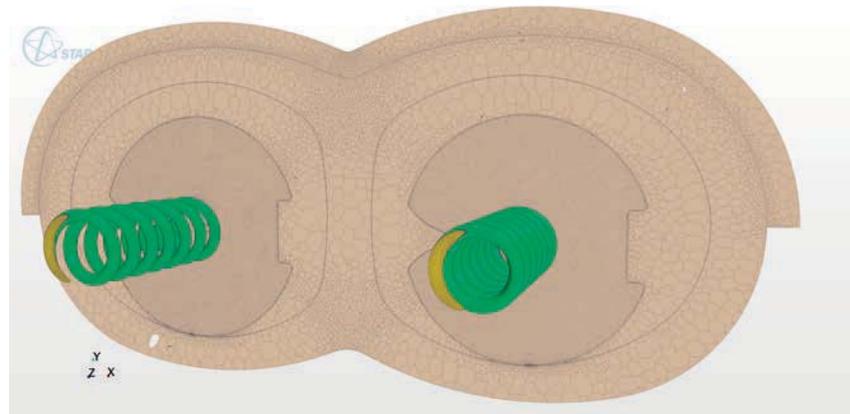


FIGURE 3: Micro-model - Meshing (source: Heraeus Noblelight / Dr. Lotta Gaab)

the molybdenum combines with oxygen in the air to form molybdenum oxide, which has a greater volume than molybdenum. This results in stress in the lamp ends, with the lamp end eventually cracking and letting air in. As discussed above, all penetration by air needs to be avoided. The lamp ends must therefore be cooled so as to maintain a temperature below 350 °C.

The geometry of the lamp is automatically imported from 3D mechanical CAD design software as step file and represents a very small part of the entire lamp. A polyhedral grid with prism layers for capturing the boundary layers accurately, and thin mesher for molybdenum spacers was created as shown in Figure 3. Energy conservation is applied to each component of the heater, and non-grey radiation heat transfer between the various components and the black surroundings that are taken into account. The ideal gas model is applied to the argon in the bulb and to the surrounding air. Thermal properties are defined as temperature-dependent functions and wavelength dependence

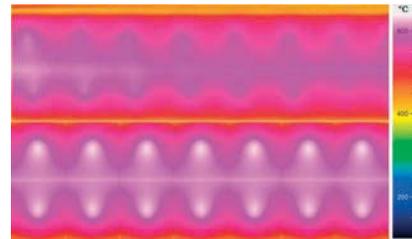


FIGURE 4: Micro-model - Temperature distribution on the quartz tube: measurement (top) and CFD (bottom) (source: Heraeus Noblelight / Dr. Lotta Gaab & Thomas Piela)

of optical parameters is considered (the simulation is performed using surface-to-surface radiation and multiband modeling capabilities). Convective cooling of the reflector, the lamp glass and the protective glass, as well as conduction in the opaque reflector were also taken into account. Because the model includes a small part of the lamp only, making the actual physical domain very narrow, periodical boundary conditions were implemented.

**APPLICATION 1**

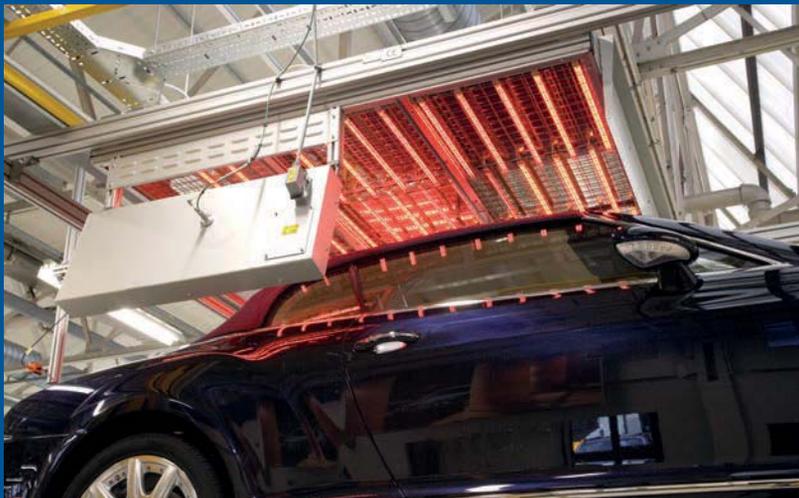
A manufacturer of steel cylinders sought a more efficient method to powder-coat the product. The previous method, a gas-heated air oven, was 30 meters long, taking up valuable production space. The company replaced it with an infrared oven from Heraeus Noblelight. The size was reduced to less than one-fifth of the size of the old oven. The infrared lamps are contoured to match the shape of the cylinder, allowing even heat application and curing. Such a system can be designed and optimized by means of CAE. (Source: Heraeus Noblelight)

Theoretical values were compared with experimental data in order to validate the models. Quartz glass and filament temperatures were measured with a thermo graphic camera or with thermocouples. Since the temperature variations of the filament are very rapid in transient state, the time response uncertainty is large. Therefore, validating CFD results against experimental data is more reliably done in steady state. STAR-CCM+ results for the filament and quartz glass temperatures in steady state compared very well with experimental measurements for the same power density, as shown in Figure 4. For example, the temperature measured on the filament was  $T_{\text{filament - measured}} = 1837 \text{ }^\circ\text{C}$ , and the simulated value  $T_{\text{filament - CFD}} = 1821 \text{ }^\circ\text{C}$ . Similarly the temperature measured on the quartz glass,  $T_{\text{quartz glass - measured}} = 625 \text{ }^\circ\text{C}$  is very close to the predicted value  $T_{\text{quartz glass - CFD}} = 643 \text{ }^\circ\text{C}$ . The difference between experimental and computed data was found to be always less than 5%. This validated model allows for an accurate estimation of the heat flowing towards the glass of the tubes and of the temperatures of different emitter components.

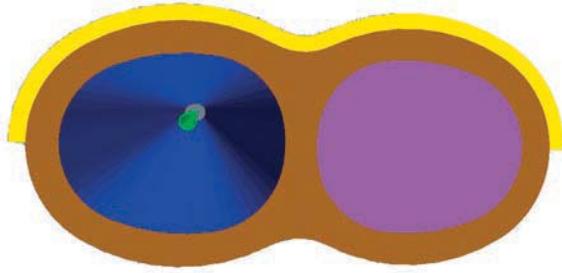
The main drawback of the micro-model of IR emitters is the large number of cells for a small physical domain. Furthermore, the numerical infrastructure is usually limited. On the other hand, the industrial applications of our customers are becoming larger in terms of design and number of built-in emitters, and more complex and demanding. Companies are progressively seeking industrial solutions through the extensive use of CAE for the optimization of product development and processes in order to predict the performance of new designs before they are even implemented or manufactured.

### **MACRO-MODEL – A PHENOMENOLOGICAL MODEL FOR COMPLEX APPLICATIONS**

To meet the needs of our customers, we derived and validated a simpler model of emitter (macro-model) which still contains all the physics information. The macro-model focuses on the interaction process between IR lamps and systems or environment; it is consistent with experimental results and requires fewer cells for CFD calculations. The geometry of quartz glass is kept the same but the filament is replaced with a hollow cylinder. As the lamp filament consists of a large number of loops that are very close to one another, its representation as a hollow cylinder in three dimensions is an educated approximation of the original design. However, this representation

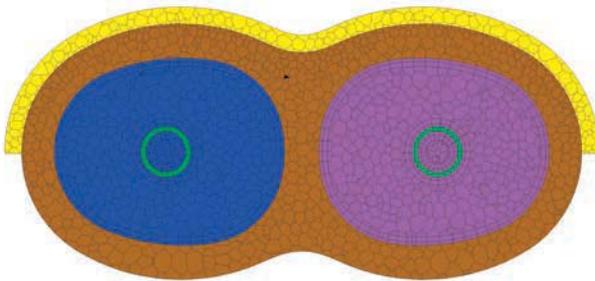
**APPLICATION 2**

Two purpose-designed infrared heating systems from Heraeus Noblelight are helping to ensure a perfect fit and to increase longevity of the headliner interior leather trim on the Bentley Continental's four-door and two-door car models. Positions, lamp types and energy density can be optimized using CAE. (Source: Heraeus Noblelight)

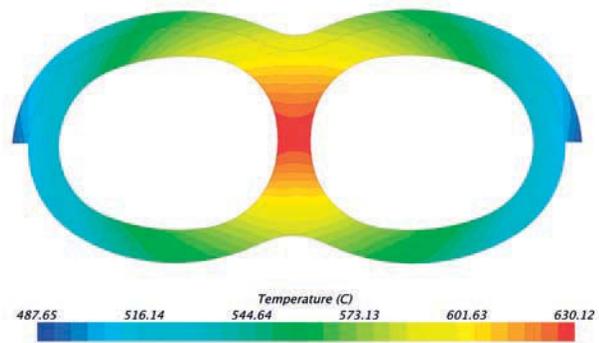


**FIGURE 5:** Macro-model - Geometrical set-up (source: Heraeus Noblelight / Dr. Larisa von Riewel)

Applied from the concept definition to the product release, already experimentally validated CAE methods have become a powerful tool to decrease costs, shorten the design cycle, increase the quality of the end product, allow for flexibility in the development process, and finally, strategically drive innovation.



**FIGURE 6:** Macro-model - Meshing (source: Heraeus Noblelight / Dr. Larisa von Riewel)



**FIGURE 7:** Quartz glass temperatures computed with the macro-model for an energy density of 96 W/cm (source: Heraeus Noblelight / Dr. Larisa von Riewel)

involves in principle a greater tungsten volume than the real helix-shaped filament and for a given amount of supplied electrical power, the filament temperature is overestimated. To solve this issue, two conditions are imposed on the filament geometry:

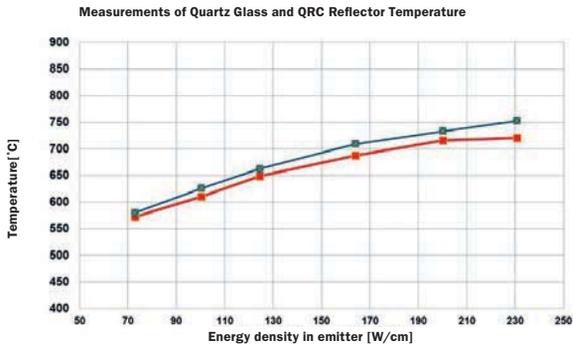
1. The outer surface of the hollow cylinder has to be equal to the surface of the helix filament (Stefan-Boltzmann law for grey radiation).
2. The hollow cylinder and the actual wire must have the same mass.

From these two constraints, the inner and outer diameters of the filament can be estimated and the geometry defined. The actual computational domain is large; periodical boundary conditions are not needed, but symmetries are defined where necessary. As with the previous model, energy conservation and non-grey radiation heat transfer between the various components are taken into account. For verification and validation purposes,

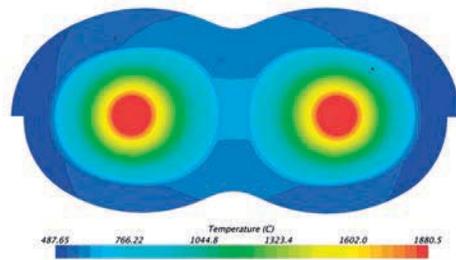
the simulated filament and quartz glass temperatures were compared to experimental values (see Figures 7 to 10).

A very good agreement between CFD and experimental results was found. The quartz temperature on the lower part of the emitter was measured at 620 °C (+/- 3%) for an energy density of 96 W/cm, and predicted at 607 °C (+/- 3%) by the numerical simulation. Another very important parameter for the stability of thermal processes is the reflector temperature. The IR emitters with Quartz Reflective Coating (QRC) reflectors are often integrated in vacuum chambers to assist Rapid Thermal Processing (RTP). The environment temperature in those applications is usually reaching 1000 °C, therefore a stable IR system, including an emitter and a reflector resistant to elevated temperatures, is necessary. Measurements of QRC

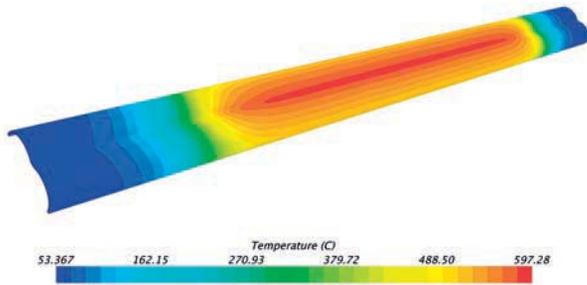
temperatures in vacuum systems are very tedious, making modeling the only practical solution available. With the self-developed macro-model, such complex configurations can be analyzed; the reliability of the model was confirmed by the comparison between the computed reflector temperatures at the top of the emitter, 590 °C (+/- 5%), and the experimental measurement, 600 °C (+/- 5%), performed either with a pyrometer or a pilot tube. The last significant parameter that needed to be checked against experimental results is the filament temperature, which sets the spectral window. The filament temperature depends on the energy density and the filament material. For 96 W/cm, it was measured at 1837 °C (+/- 3%), which was once again in very good agreement with its numerical counterpart, at 1880 °C (+/- 5%), still within the range of acceptable accuracy.



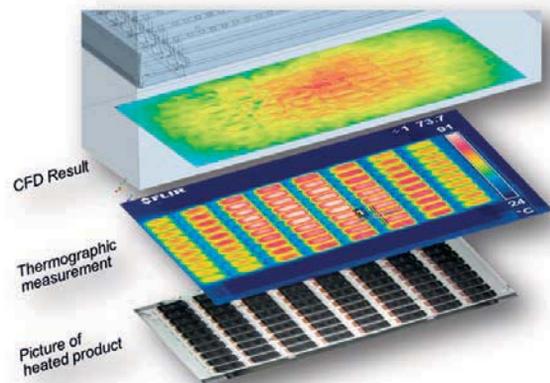
**FIGURE 8:** Quartz glass (blue line) and QRC (red line) temperatures vs energy density: The measurements were performed on the lower part of the emitter and on the reflector respectively. (Source: Heraeus Noblelight / Dr. Larisa von Riewel)



**FIGURE 10:** Computed temperature on the filaments for an energy density of 96 W/cm (source: Heraeus Noblelight / Dr. Larisa von Riewel)



**FIGURE 9:** QRC reflector temperature for an energy density of 96 W/cm (source: Heraeus Noblelight / Dr. Larisa von Riewel)



**FIGURE 11:** Temperature distribution and edge effects on a substrate (theoretical prediction and measurements) (source: Heraeus Noblelight / Dr. Larisa von Riewel)

**SUMMARY**

Using CD-adapco’s software STAR-CCM+ and mechanical design tools, we developed comprehensive 3D models (micro-models) of IR lamps, as well as large-size models (macro-models) based on phenomenological assumptions for more complex applications. The macro-model is the default model used for CFD analyses of HNG-IP infrared modules for industrial processes. For example, the numerical analysis of an IR heating system with nine emitters (100 cm length) and external cooling can predict the temperature homogeneity on a substrate. Edge effects are always an issue for nonconductive continuous large surfaces (plastics) or for substrates containing metal-plastics components. Additionally, the convective cooling of the heated surface may have a considerable contribution to the total heat management, making the qualitative evaluation of hot and cold spots in the pre-development phase a necessity to optimize the industrial process.

**CONCLUSION**

This article introduced the various types of IR heaters developed by Heraeus Noblelight, and described their design characteristics and operating principles. Special attention was given to the self-developed models of electric IR heater. The models include non-grey radiative heat transfer between the different parts of the heater, as well as conduction in the reflector material and convective cooling of the surfaces. Using electrical power as the only input, the models’ predictions of temperatures were found to agree well with experimental data at steady-state conditions. The validated models are used either for investigations and improvements of emitters (micro-model) or for large scale simulations of industrial processes (macro-models).

In the last few years, it became increasingly important to not only be able to supply heat, but also to supply it in a controlled

and efficient manner. Production speed and product quality demanded precise amounts of heat. Energy costs are often an important part of production costs. Better understanding the heat transfer process has long since become an important area of engineering research. More recently, energy conservation has also become an environmental issue in itself, independent from the economic incentive involved.

From this perspective, numerical simulation (CAE) has become for HNG-IP a valuable feature, a key enabling factor in the virtual analysis and optimization of highly competitive and advanced systems. Applied from the concept definition to the product release, already experimentally validated CAE methods have become a powerful tool to decrease costs, shorten the design cycle, increase the quality of the end product, allow for flexibility in the development process, and finally, strategically drive innovation.