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3D electrical and thermal simulation of a resistance heated EFG system

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1. Introduction

The requirements in manufacturing of solar cells increased dramatically due to the ascended worldwide demand and the consequent shortage of silicon. A continuous increase of efficiency while reducing costs on the other hand, are in the spotlight of the development of future production processes.

The company WACKER-SCHOTT-Solar located in Alzenau is successfully using a procedure, which is especially designed for the manufacturing of solar photovoltaic cells. In the so called Edge-defined Film-fed Growth procedure (EFG) long and hollow silicon tubes will be pulled directly from the silicon melt. The wall thickness of such tubes corresponds directly to the strength of the finished wafers. Thanks to a laser cutting machine, that cuts wafers directly from the tube, additional material losses can be avoided.

The advantages of the EFG-technology compared to other procedures are a high productivity, the low costs of the wafers and a rapid laser-cutting process, that guarantees highly mechanical wafer strength with a low rate of material waste.
A decisive factor for the quality of wafers during the pulling process is a homogenous temperature distribution in the crystallization front along the silicon tube [2]. Any inhomogeneity temperature disturbs the pull and causes instability. The results are different thickness distribution along the silicon tube. If the interference is too large the pulling process must be interrupted.

For further improvement of the production process to gain more reliability and efficiency the Institute of Electrotechnology of the Leibniz University of Hannover creates a three-dimensional model of the entire melting furnace. With the help of this numerical model influences on the homogeneity of the temperature distribution at the crystallization front should be investigate, because of variations in the construction of the facility.

Right now induction heated melting furnaces are in use and create a octagonal tube form [1]. For these facilities a numerical model already exists [2]. In this work carried out studies show detailed the high expense of optimization of inductive operating systems. The new plant is supposed to surpass his predecessor, especially in the production process optimization.

In addition to the production of a 12 sided also referred dodecagon instead of a 8 sided tube that heighten significantly the yield per pull, the required energy for the melting process is provided by an individually adjustable 12-zoned resistance heating element and not by an induction coil.

An immediate benefit is the direct influence on the required process energy in the individual tube sections and thus on the resulting temperature distribution. The possibility of the adjustment setting means a controlled influence of the resulting thickness of the silicon tube in different areas.

With the help of the new numerical simulation model the further development of the system should be accelerated and also cost-effective parameter studies will be performed in less time. Not only the increase of quality of the product is in the front of interest, but also to obtain more information about the physical processes during the melting sequence.

2. Development of the numerical model

The modeling is currently divided in two steps.

The first step is the generation of an electromagnetic three-dimensional model of all heat sources. The second step is to create a thermal model of the actual oven geometry.

2.1 Step 1

The heat sources of the EFG-system consists of a main heater to melt the silicon and an afterheater positioned above the crystallization front of the tube. An example from this part of the geometry model is shown in Fig. 1.

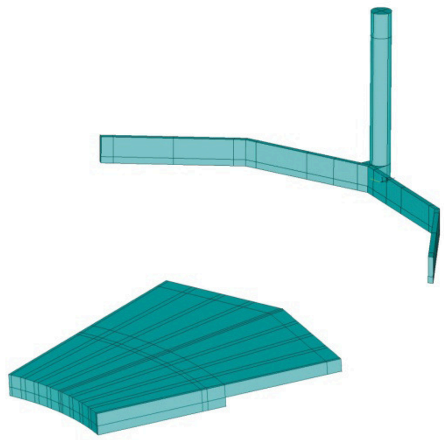

Fig. 1. 3D-view: main- and afterheater

In accordance with the experimentally determined specifications the needed supply voltage is applied on the points of delivery and the results of the Joule's heat source distribution are put element-wise into a file. These results will later be imported for steady state analyses in the radiation model of the entire melting furnace in Step 2.

The challenge in the future development is the complete linkage of both individual models to receive a temperature distribution as a function of an electric-magnetic and thermal coupled iteration procedure. This will also take the backlash of the entire model on the heating elements into account. Currently, due to the different phases in design of model parts and the current state of model development, such an approach is not possible. The limits of acceptable computing time on current systems would be exceeded.

2.2 Step 2

The main part of the simulation effort concerns the thermal model. This part contains the entire furnace geometry considered as relevant for the crystallization process. A three-dimensional cross-section of the model is shown in Fig. 2.

Silicon has its melting point at 1410°C. Taking into account the Stefan-Boltzmann law, which states that the maximum power density grows with the fourfold power of the absolute temperature of the radiator, one main invention focus is about the development and optimizing use of a suitable radiation model. This focus is with regard to the proportion of radiation throughout the heat transfer process permitted.

2.2.1 Radiation method

In the commercial software package ANSYS ® the method of "Radiosity Solver" comes into operation. This latest approach to simulate the radiation exchange offers among other the advantage of easier creation of radiation surfaces, temperature dependent emission levels and the application of symmetry effects. A much more important item, as mentioned above, is the executability of larger models, as they are possible in direct comparison to the older "aux12" method.

Equation (1) defines radiation between two surfaces:

$$Q_{12} = A_1 F_{12} \epsilon_1 \sigma (T_1^4 - T_2^4), \quad (1)$$

where F_{12} represents the form factor of fraction of total radiant energy going from surface 1 to 2

The Radiosity Solver method calculates the temperature distribution in a segregated, iterative fashion for radiation and heat conduction-until convergence is achieved. These method reverts to a defined viewfactor-matrix with the constants F_{ij}. The "aux12" method on the other hand uses an effective heat conduction-matrix. This matrix contains all information about geometric orientations, shapes and emission levels of the numeric model. The calculation of the radiation needs no segregated substeps and shares the same routine with the heat conduction. The determination of this effective matrix is very memory and computation intensive, so with respect to the aforementioned complexity of the arrangement, the required memory and time is not available.

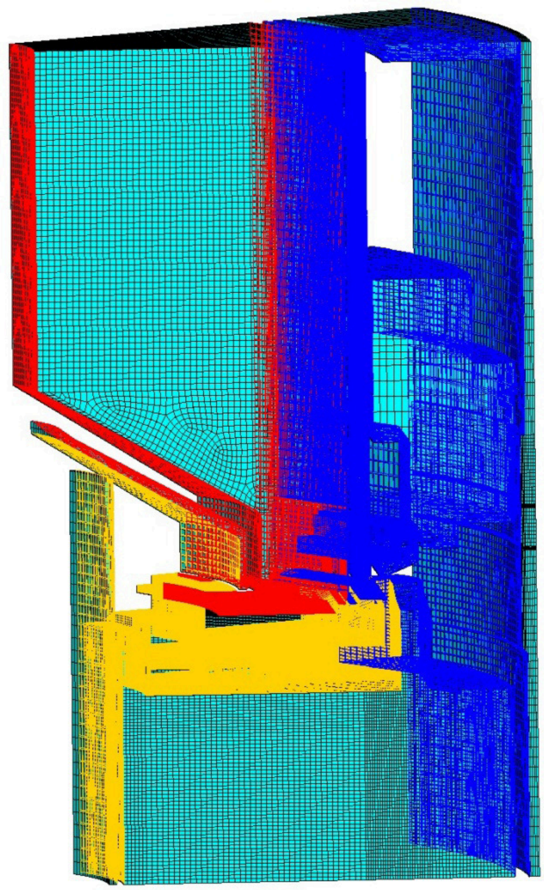

Fig. 2. 3D cross-section: finite element mesh and enclosure arrangement

2.2.2 Radiation model

For the radiation model all surfaces must be covered with the appropriate material emission ratio. Due to the parameterized single volume structure, which allows easier following adjustment of the simplified geometry, one must be aware that the emission ratio only covers external surfaces. In the case of a selection of a surface area within the general arrangement it is possible that the calculated temperature distribution shows unsymmetrical variations in the affected parts.

Furthermore, a division into so-called enclosures and the establishment of the radiation symmetry conditions has to be carried out.

In Fig. 2 an exemplary distribution of the enclosures is shown. By the use of these enclosure-zones a decoupling of different model zones can be obtained. The program takes all single surface elements of the arrangement into account and calculates a solution for the viewfactor-matrix, although a intervisibility through the geometry is not given. This leads to a larger viewfactor-matrix and also to longer computing times. With the division into different enclosure-zones only surface elements with equivalent factor assignment are taken into account. One may decide how much a structural restructuring of the model is possible and suitable.

According to the status of current desktop systems it is impossible to create a finite element system of such complexity that covers the entire scope of the silicon tube. However, it is important not only to examine that part of the model resulting from the repetitive form of the dodecagon, but also the adjacent cuttings. These border parts must also be taken into consideration because a significant proportion of the radiation from the adjacent areas reaches the surfaces of the actual cut.

Using the radiation symmetry option the parts of the generated furnace system can be repeatedly created. The advantage of this method is that only the surface of a part will be mirrored, but not the assigned material values or the resulting matrixes. A recalculation of temperature distribution will not take place.

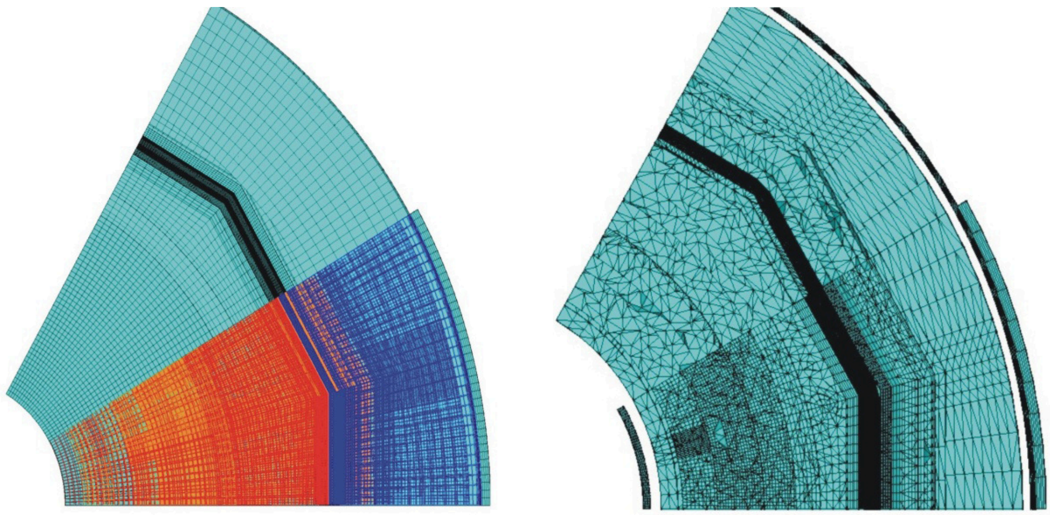

Fig. 3. Radiation symmetry settings: without reduction on the left; with reduction on the right

Only with the repeated image of the original calculated thermal distribution the output surface will be formed. This reduces the computing and storage complexity immense and the operability of the numerical model remains.

For further relief of system resources an adjustment of the radiation surfaces is possible. But the analysis showed that a reduction of the surface structure without proper verification should not be applied, since the reached quality of the manual meshing procedure is disturbed.

A reduction results in irregular distortions followed by deviations in the calculation of the viewfactors. The difference can be taken from Fig. 3.

2.3 Optimization

At computing times next of several days it must be ensured that the feasibility of the numerical model is certainly given to avoid unnecessary delays. The optimization of the commands for the exchange of radiation and for the iteration settings influences not only the quality of the results, but also the time which is needed to obtain the results.

The calculation of the radiation exchange with the environment is carried out by the Gauss-Seidel method. Each numerical radiation model has its own specific radiation matrix, so that it is worth the effort to identify the individual parameters instead to use the default values.

A successful optimization through adaptation of the iteration settings and radiation commands is shown in Fig. 4. The upper part of the picture shows the iteration history of an independently operating iteration algorithm.

If one tightens the tolerances in this example furthermore, the very slow convergence characteristics will change and become a oscillating course with no stationary solution (Fig. 4 stage 0). A steady state solution exists if the value of the curve HEAT L2 drops below the value of the curve HEATCRIT. If this condition is reached, the value is within the defined tolerance range.

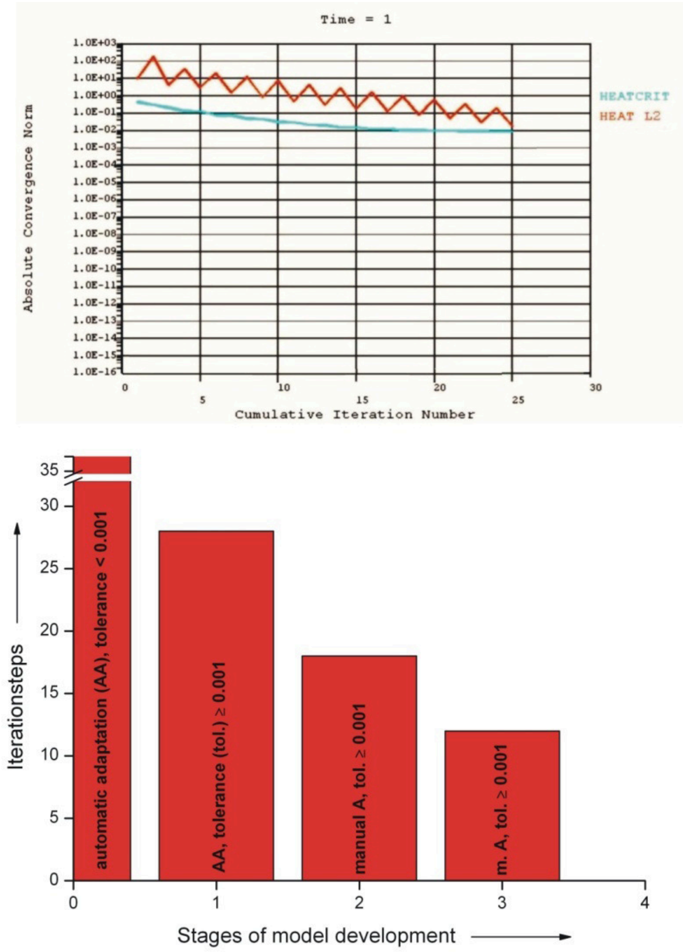

Fig. 4. Iteration history: with automatic adaptation (top); results after manual adaptation (bottom)

In the process of adaptation it can be clearly seen an advancement. The number of iteration steps decrease continuously. In stage 3, compared to stage 2, also an adaptation of the radiation commands takes place.

3. Conclusion

Since the model is still in the early phase of development, there is still a considerable amount of work to do in order to achieve a complete verification of the numerical model.

At this time, however, the modeling of the geometry of the melting furnace is almost finished and there is the determination and adjustment of the boundary conditions. The results obtained so far show a qualitative good match of the calculated numerical data with the previously experimentally determined values by WACKER-SCHOTT-Solar.

Investigations on reduced fragment-models of the general arrangement point out that extensive optimization options exist in the current radiation model and in the iteration settings of the software. The application of results of this investigation to the general arrangement so far led to the expected qualitative improvements.

4. References

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