Virtual Temperature sensing on Butterfly Valve plate

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***Abstract*—Control valves are used in downstream operation to regulate the pressure in process chambers for the production of semiconductors. Depending on the opening angle of the valve plate, the conductance is changed and thus the flow and the pressure in the process chamber are changed. During a process, different gases and chamber pressures are required in the process chamber. These process gases are mainly thermally activated and begin to condense when they come into contact with surfaces below the condensation temperature, which subsequently leads to unwanted deposits.**

The valve plate for regulating the flow is one of these components, which is constantly at risk of being in the condensation temperature of the gases and is thus affected by a constant build-up of deposits. The influence of the deposited layer changes the control behaviour of the valve, which has negative influences on the process. In extreme cases, the deposit can become so large that the movement of the valve is restricted or can no longer be closed and fails, resulting in machine failures with high costs.

In the present work, a butterfly control valve of the 61.3 series from VAT Vakuumventile AG, which is used in the semiconductor industry, is thermally analysed. The aim is to develop and evaluate a method to determine the temperature of the valve plate without placing a sensor directly on the valve plate or on an surface which has directly contact to the vacuum.

The chosen approach is to place temperature sensors on the valve in such a way that the temperature of the valve plate can be estimated by using a thermal model. The model is described by using the three heat transfer phenomena. Furthermore, the model is validated by several iterations of FE simulations and laboratory tests in order to increase the accuracy step by step.

***Index Terms*—Model-based temperature measurement, Non-invasive temperature measurement, Simulation-based temperature measurement, Butterfly control valve**

I. Introduction

THE model-based approach for temperature measurement requires a physical model that represents the thermal behavior of the valve. As an input for the model, a temperature difference is used, which changes depending on the variable to be determined, the valve temperature. To achieve this, a model of the valve must be created based on the three heat transport phenomena. At the same time, suitable positions for the temperature sensors must be found without them coming into contact with the vacuum and thus negatively influencing the semiconductor processes.

II. Methods

Heat conduction

$$\dot{Q}_{cond.} = \frac{\lambda}{l} \cdot A \cdot \Delta T. \tag{1}$$

describes the heat transport in a solid and depends on the thermal conductivity λ of the material, the length l, the effective cross-sectional area A and the temperature difference ΔT.

Convection

$$\dot{Q}_{conv.} = \alpha \cdot A \cdot \Delta T \tag{2}$$

describes the heat transfer from a solid to a fluid. The heat transfer coefficient α is calculated from

$$\alpha = \frac{\lambda_F}{\delta_F} \tag{3}$$

the thermal conductivity of the fluid λ_F and the layer thickness δ_F. According the heat radiation all bodies with a temperature above 0 K, emit energy in the form of electromagnetic waves. According the law of Stefan Boltzmann

$$E = \sigma \cdot T_R^4 \tag{4}$$

the radiated energy density corresponds to the proportionality factor of the Stefan Boltzmann constant σ and the absolute temperature T_R which is proportional to the fourth power.[1][2]

In order to describe the thermal behaviour of the valve based on the preceding transport mechanisms, a suitable modelling method must be chosen. The following table shows the analogies between electrical and thermal quantities.

TABLE I
ANALOGIES BETWEEN ELECTRICAL AND THERMAL QUANTITIES [3]

el. values		**thermal values**	
el. potential	ϕ	temperature	T
el. voltage	U_{el}	temperature difference	ΔT
el. current	I_{el}	thermal power	$\dot{Q}$
el. resistance	R_{el}	thermal resistance	R_{th}
el. capacity	C_{el}	thermal capacity	C_{th}

These analogies allow the application of Ohm's law

$$U_{el} = I_{el} \cdot R_{el} \tag{5}$$

to thermal equations

$$\Delta T = \dot{Q} \cdot R_{th}. \tag{6}$$

Based on a thermally steady-state Finite Element Analysis (FEA) simulation using ANSYS, the valve housing T_H and the bearing sleeve T_{BS} were identified as temperature measurement points that serve as input parameters for the model. The valve housing is actively heated by electrical PTC (Positive Temperature Coefficient) heaters and therefore always has the highest temperature potential within the valve. In contrast, the bearing sleeve is separated from the housing by the bearing block, which is made of a low thermal conductivity plastic material. Consequently, the temperature of the bearing sleeve is influenced not only by the heat flow from the bearing block but also by a second path that runs through the valve plate. This means that the temperature of the bearing sleeve is influenced by its thermal dependency on the valve plate.

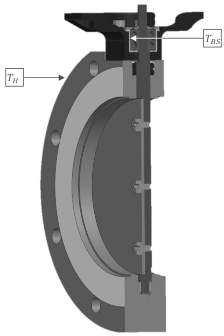

Fig. 1. Sectional view of the valve

In the next step, the heat paths from the housing to the bearing sleeve, as shown in Figure 1, were identified and described using heat conduction ((1)) and Ohm's law for thermal conduction ((6)). This information was used to create the following equivalent circuit diagram shown in Figure 2.

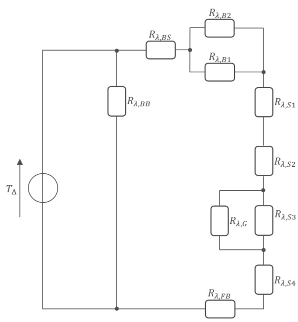

Fig. 2. Thermal equivalent circuit for heat conduction

Finally, all components of the above-mentioned network that directly interact with the environment or the process were supplemented with the convection heat transfer mechanism to create a complete network as shown in Figure 3.

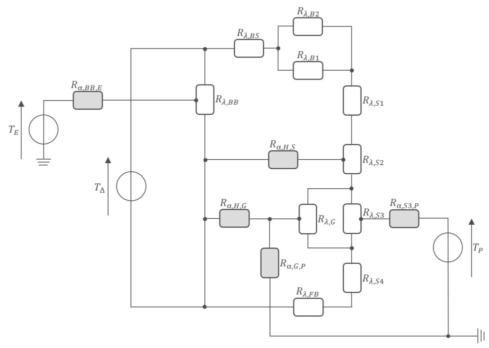

Fig. 3. Total thermal equivalent circuit

Radiation heat transfer is neglected in this case because the temperature difference between individual components is small, leading to a negligibly small radiated power.

III. Measurements

The static test setup depicted in Figure 4 allows for the thermal analysis of the valve under various system pressures and valve positions.

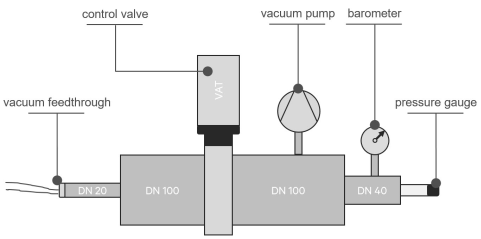

Fig. 4. Experimental set-up for thermal analysis

The vacuum feedthrough allows the integration of temperature sensors into the vacuum chamber to measure the valve plate temperature during the experiment. Using a vacuum pump, the setup is evacuated and brought to the desired system pressure. The barometer and pressure gauge allows the monitoring and recording of the pressure. The subsequent measurement shown in Figure 5 illustrates the temperature profiles of the valve plate and the bearing sleeve as a function of the valve position. To ensure that all transient components have decayed, the time between each adjustment of the valve position is two hours, corresponding to a vertical line in the graph.

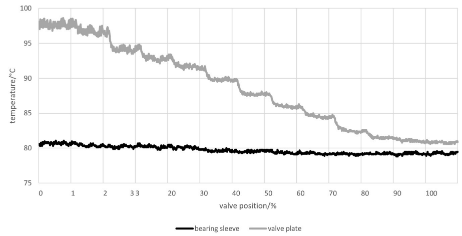

Fig. 5. Total thermal equivalent circuit

In the measurement, it can be seen that the valve plate temperature decreases as the opening angle increases, starting from the closed position. The temperature at the valve position of 0 % is 97.7°C, and decreases to 80.8 °C at a position of 100 %, resulting in a temperature difference of 16.9 °C. In comparison, the temperature of the bearing sleeve decreases from 80.7 °C to 79.3 °C. Experiments conducted at different ambient pressures exhibit similar behavior.

IV. Conclusion

The results of the laboratory experiments demonstrate a measurable correlation between the temperature of the valve plate and the temperature of the bearing sleeve. Consequently, the thermal analysis has shown that it is possible to implement a non-invasive temperature measurement to avoid integrating a temperature sensor into the critical vacuum area. This opens up the possibility of integrating the valve plate temperature measurement into the existing product without the need for modifications to the process-critical components.

However, it has also been determined that the complete thermal modeling of the valve assumes extremely complex dimensions that are no longer manageable analytically. In particular, convective heat transfers, which can only be approximated through experiments or numerical methods, make the use of a purely analytical method impossible. Therefore, for precise modeling that takes into account transient processes and process conditions, numerical modeling is required.

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