Condition Monitoring System for Steam Ejector Vacuum Pumps

Digital technologies are transforming industry at all levels. Steel has the opportunity to lead all heavy industries as an early adopter of specific digital technologies to improve our sustainability and competitiveness. This column is part of AIST's strategy to become the epicenter for steel's digital transformation, by providing a variety of platforms to showcase and disseminate Industry 4.0 knowledge specific for steel manufacturing, from big-picture concepts to specific processes.



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"Especially in the production of higher-quality steel grades, the vacuum treatment of liquid steel takes a prominent position among secondary metallurgy processes due to its versatile nature. To produce the necessary high vacuum, pump systems comprising steam-ejector vacuum pumps or mechanical vacuum pumps are used in modern, efficient secondary metallurgy plants for the vacuum treatment of steel."[2] This article deals with the application of a condition monitoring system for a vacuum system of steam-ejector type.

An end vacuum level above the liquid steel surface of around 1 mbar is desirable both for degassing and decarburization depending on the steel grade being treated. In addition to the end vacuum, the pump-down time is another criterion in view of effective plant usage and media consumption. To this end, a perfectly operating vacuum pump is essential for vacuum steelmaking.

However, the vacuum pump is continuously exposed to dust-laden process gases from the vacuum tank or vessel in combination with steam. And it operates in the rough environment of a secondary metallurgical plant. In case of a steam-ejector type vacuum pump, a declining performance might be the result of worn nozzles, leakages, bad media conditions, dirt and many other reasons. As this type of vacuum pump is a large-volume plant with extensive piping and valves, troubleshooting can be a demanding and time-consuming task.

Therefore, vacuum steelmakers may appreciate a tool to display deviant behavior, predict maintenance demand and identify problems as precisely as possible. SMS Mevac's condition monitoring system (MCMS) consists of a set of additional instruments and a level 2 kind of software that cyclically evaluates the data flow from all available field instruments via programmable logic controller (PLC) with the objective to provide:

- Diagnostics.
- Problem detection.
- Problem isolation.
- Observation of problem development.
- Expandability.
- Updateability.
- Feasibility.

MCMS is currently in trial operation in a German steelmaking plant. At the beginning of development, a system identification approach, "model identification," prevailed over a pure data-mining approach with regard to a practicable and quickly realizable solution. The current system's behavior is compared with the result of models trained under normal conditions to tell if, currently, vacuum pump and subsystems down to the measuring device behave differently than normal. Maintenance advice is derived from a logical combination of specific model results.

Steam Ejector Vacuum Pumps (SVP)

The main task of an SVP is the evacuation of huge volumes of gas in order to reach and maintain a pressure of less than 1 mbar in a few minutes. During vacuum treatment, process gases, especially the ones resulting from the decarburization or degassing processes, are sucked off.

Steam-ejector type vacuum pumps are the most common in secondary metallurgical vacuum plants like vacuum degassing (VD) or Ruhrstahl-Heraeus (RH) plants. As shown in Fig. 1, an SVP typically consists of four steam ejector (stages), SE1 to SE4, connected in a series. Pressurized overheated steam is released through a motive nozzle, causing a suction effect as the process gas is quasi-entrained by the accelerated steam.

In operation, the steam ejectors sustain the pressure gradient between atmosphere and the vacuum above the steel ladle in a tank or below an RH vessel, i.e.:

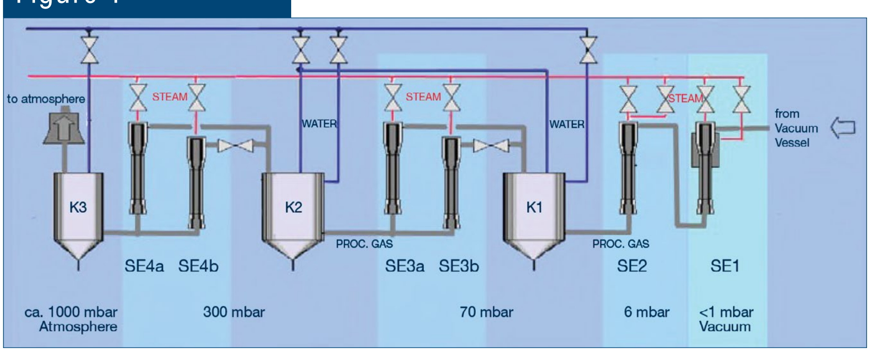
$$P_{\text{atmosphere}} - P_{\text{vacuum}} = \sum_{i=1}^{4} \Delta P_i \qquad \text{(Eq. 1)}$$

Each ejector stage provides a specific compression ΔP_i. As shown in Fig. 1, the atmospheric ejector stage 4 compresses from about 300 mbar to atmospheric pressure; ΔP_4 becomes about 700 mbar. The subsequent ejector stage 3 compresses from about 70 mbar to 300 mbar; ΔP_3 becomes about 230 mbar. Ejector stages 3 and 4 typically consist of two parallel steam ejectors a and b. For steam saving, one of the two is switched off once ejector stage 2 is on. Between two ejector stages, a condenser removes the steam of the respective previous stage with one exception. Due to the low pressure of about 10 mbar between ejector stages 1 and 2, condensation of the steam is not possible and, therefore, condenser K1 before stage 3 has to wash out the steam of two ejector stages. The condensers are fed with condenser cooling water from the top. The purpose is to condensate the steam, i.e., remove from the process gas. The condenser cooling water is drained down to the so-called hot well below the SVP. Without condensation, the steam would represent an additional load for subsequent stages. Therefore, not only the performance of the individual steam ejector but also the effectiveness of the condensation is equally significant for the overall pump performance.

Evacuation Pump-Down — At the start of evacuation, the steam valves of stages SE4a and SE4b open. Once a pressure of 300 mbar is reached, the steam valves of stages 3a and 3b open simultaneously. At 70 mbar, SE2 follows and at 6 mbar SE1 is turned on to pump-down to deep vacuum level.

Meaning of "Vacuum Stage" — Evidently the SVP changes its configuration whenever the next steam ejector is turned on. Before the steam is turned on, a steam ejector practically represents a pipe only. So the "vacuum stage" describes the constellation of the vacuum pump and is to be distinguished from the steam ejector stage. Table 1 describes their relation.

Figure 1



Functional sketch of a 4-stage vacuum pump.

Table 1

Vacuum Stage vs. Ejector Stage and Individual Steam Ejectors in Operation (=x)

	Ejector stage 4		Ejector stage 3		Ejector stage 2	Ejector stage 1
Steam ejector / Vacuum stage	SE4a	SE4b	SE3a	SE3b	SE2	SE1
1 (start) … 300 mbar	x	x				
2 … 70 mbar	x	x	x	x		
3 … 6 mbar	x		x		x	
4 (deep … < 1 mbar vacuum)	x		x		x	x

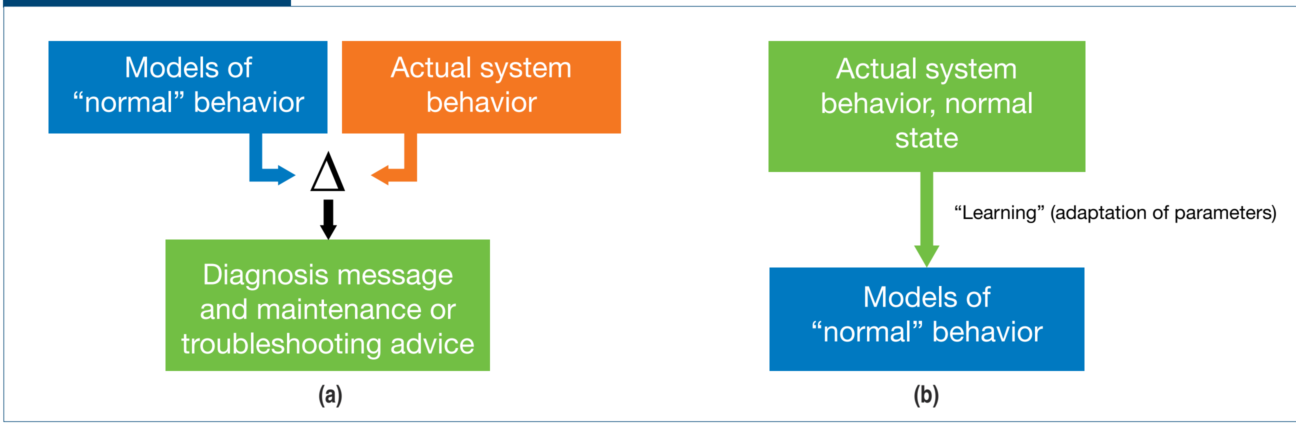
Principle of MCMS

The basic principle of SMS Mevac's approach is comparing the actual system's behavior with a normal state. The normal state is provided by so-called "models," which shall reflect the normal condition. Initially, this approach indicates that the vacuum pump and subsystems down to the measuring device behave differently compared to the behavior of the corresponding model on identical input data. In the simplest case, the model signals red, yellow or green depending on the degree of deviation. Red denotes an intolerable situation. More specific results, diagnosis and advice to the maintenance personnel depend on the model itself and also can be derived from a combination of models.

The evaluation is based on the processing of cyclic data provided by an augmented set of field transmitters.

Model Training — The pre-configured models have to be trained with data from treatments. Thus

Figure 2



Identification and comparison (a) and learning, adaptation of model parameters (b).

those treatments will practically become a "frozen" reference. At any time, the parameters can be replaced or updated by retraining with data of the current or recent treatments.

Measuring Devices to Feed the Model — While only a few measurements are sufficient for normal operation, for better diagnostics an extended set of transmitters is required for MCMS, as shown in Table 2.

In addition to directly SVP-related measurements, there are also process-related data to be taken into account. The behavior of the SVP depends on the amount and quality of the process gas, e.g., decarburization vs. degassing treatments:

- Offgas: composition (CO, CO_2, O_2), offgas flow.
- Process related: Argon, O_2 flows.

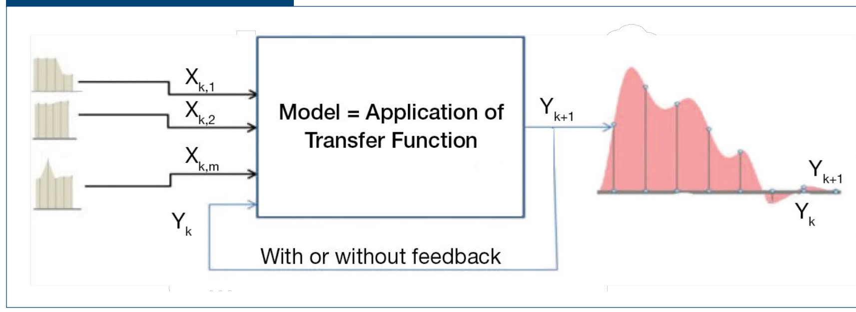
Table 2

Measuring Devices in Steam Ejector Vacuum Pumps (SVP), Standard and Extended Set

Scope	Measuring device	MCMS-related purpose
Standard measuring equipment	Inlet steam — flow, pressure, temperature	Elementary checks
	Total CCW — flow, pressure, temperature	
	Vacuum pressure (abs.) at low pressure side of SVP	
	Condenser's outlet water temperature and level monitoring	
	Hot well water level monitoring (safety related)	
	Local pressure indication at steam valves (not wired to programmable logic controller)	
Extended set or transmitters for diagnostic purposes	Intermediate vacuum pressures • Between steam ejectors SE1 and SE2 • At condenser 1 • At condenser 2	Failure to reach the total suction pressure is often due to back-pressure in an intermediate stage, but is not always recognized due to the lack of intermediate pressure measurements
	Steam pressure at outlet of steam valve for steam ejectors (SE1, SE2, SE3a/b, SE4a/b)	The steam pressure before entering the steam nozzle of each steam ejector is crucial for its proper function. The standard installed local pressure gauges are often defective and useless after a short time.
	Steam flow at outlet of steam valve for steam ejectors (SE1, SE2, SE3a/b, SE4a/b)	At constant steam pressure, wear on the steam nozzle (enlargement of the neck diameter) can be recognized by an increased steam flow
	Two measurements (main and side flow) for each of the three condensers	Each condenser has one or two connections for the cooling water supply. The correct flowrate is decisive for the condensation of the steam and the resulting intermediate pressure in the condenser and thus has a decisive influence on the suction pressure, which can be achieved by the downstream stage.

In total, the number of analog values from field transmitters and derived values is about 100. Additionally, there are binary values like valve position and others.

Figure 3



Model as transfer function.

Modeling

Transfer Function — An MCMS model is simply a transfer function and processes one or more input values; for example, a model for water outlet temperature as a function of two values, namely, value 1 = inlet temperature and value 2 = water flow.

The values are fed to the model via time series, which means sampled values at a given sampling rate of, say, 2 seconds. The model returns values at the same sampling rate by evaluating the formula:

$$Y_{k+1} = \sum_{i=1}^{n} a_i Y_{k-i} + \sum_{j=1}^{m} \sum_{i=1}^{n} b_{ij} X_{k-i,j} \qquad \text{(Eq. 2)}$$

with

k = number of sampled value since start of treatment,
m = number of input value (for example $m = 2$),
n = order of the model,
X_{jk} = the sampled input of value j ($j = 1$ to m),
Y_k = the calculated Y of previous iteration k and
Y_{k+1} = the newly calculated Y.

Thus, the model response Y_{k+1} depends both on inputs X_k and Y_k calculated in the previous iteration k_{-1}. In this shape, the model is of differential, "relative" type, calculating how Y will develop starting from the actual value. With parameters $a_i = 0$, i.e., without feedback in Fig. 3, the model becomes an "absolute" model in which Y only depends on the input values X with parameters $b'_{ij} \neq b_{ij}$.

Fig. 3 illustrates how a single model works. It is fed by time series of discrete input values and calculates the time series of a discrete output value. Depending on the sampling rate, one obtains a semi-continuous signal on the right. Now one compares the current Y and the actual value and can draw conclusions from the deviation of model Y and current, i.e., measured Y (Fig. 4), and produce a traffic light signal depending on the degree of deviation.

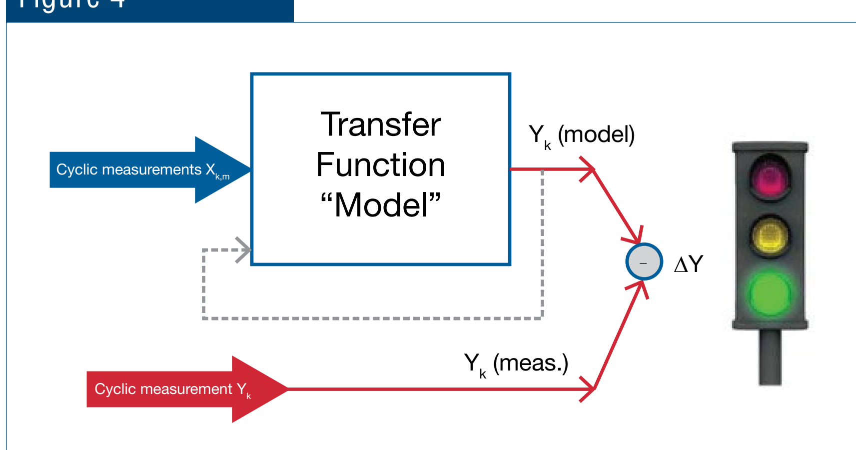
Setup Models — For optimum similarity of model response and actual system response, model configuration and subsequent training is significant. The MCMS tool permits model creation, configuration and training, i.e., updating of parameters.

A model is setup as follows:

1. One output value Y, one or more input values X — The input values X are typically cyclic data from:

- Field transmitter readings, such as "steam flow measurement."
- Arithmetic combination of field data, such as total steam flow from all individual measurements.
- Mathematical transformation such as log().
- Pseudo data, such as constants.
- Fixed formulas applied to field transmitter readings, such as critical steam pressure = f(steam temperature).

Figure 4



Comparison of model and actual value.

2. Validity range pump stage — As said earlier, the SVP changes its configuration whenever the next steam ejector is turned on. Therefore, it can be necessary to define a validity range of the respective model in terms of the vacuum stage (Table 1).
3. Model order — The order denotes the number of time constants and affects stability, oscillating or monotonous behavior.
4. Relative or absolute model — As said earlier, the "relative" model calculating how Y will develop starting from the actual value. This is achieved by feedback of the calculated Y. Without feedback in Fig. 3, the output of the model practically — depending on the model's order — becomes a linear combination of the input values' "absolute model."
5. Define red-yellow-green ranges — The maximum percentage or absolute deviation of model and measured value have to be defined for the cases model > measurement and model < measurement individually. This way, the model gets a binary output, say, "okay"/"not okay" plus "yellow" state.
6. Define diagnostic messages and advice message — For the "out-of-range" case, a diagnostic message and further maintenance or repair advice messages can be linked to the model. These messages can further be connected to dedicated "traffic light" controls in the plant mimic.
7. Assign model to one or more groups (e.g., "Cooling Water") — For display purposes, it is useful to assign models to one or more groups. One and the same model might occur in several groups; for example, a model setup for checking the consistency of water flow data from field transmitters might occur in a group called "Instruments Consistency" and further in a group called "Cooling Water," etc.

Logical Combination of Models — For more specific diagnostics, it is possible to logically combine "analog" models and equally assign diagnostic messages, etc., to this new type of model. By means of an and-or-not syntax, the binary red/green output of those models can be combined and one gets a new model with comparable red-green behavior.

Model Tuning — The pre-configured models have to be trained with data from treatments. At any time, the parameters can be replaced or updated by retraining with data of the current or recent treatments. For model learning, a method of system identification is applied.

Identification means finding an optimum combination of parameters $a_i b_{ij}$ with:

i = 1 to n, n = model order
j = 1 to m, m = number of measured quantities

so that the sum of squared deviations,

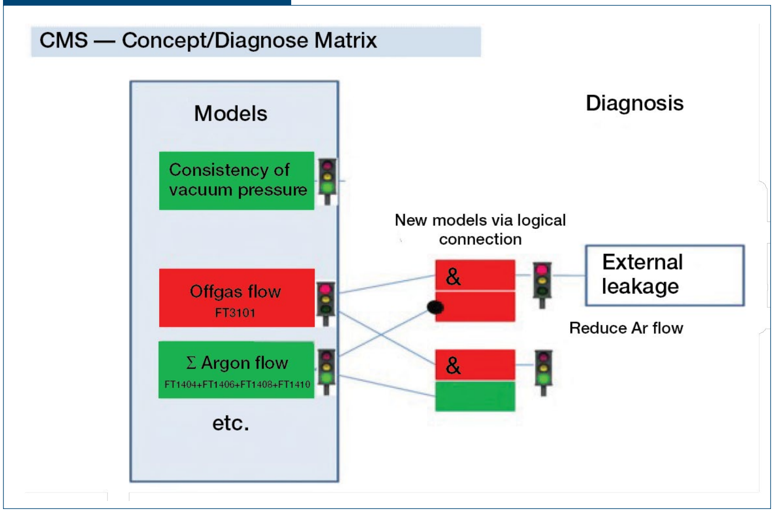
$$\sum_{k=1,N} \left(Y_{k(model)} - Y_{k(meas)}\right)^2 \quad \text{min.}$$

becomes minimum. Then, for the data used for model training, the system response will match the measured response. However, to identify the impact of a certain input value, a variation of this value is necessary. For example, a model for the outlet cooling water temperature might be set up based on the inlet temperature, water and steam flows. If the treatments used for model training show little or no variation of the inlet temperature, the model hardly can reflect the impact of a different inlet temperature. Therefore, it is necessary to permit retraining based on the given set of parameter values using treatments with a deviating inlet temperature.

Recursive Least-Squares Algorithm[1] — For best approximation, the model is trained or retrained with trends of at least one, typically many, treatments. To this end, a recursive algorithm is used. In a recursive calculation, the time series are fed step by step and parameters are adapted after each set, k, of values Y_k, X_{kj}. The important advantage is that the parameters of an existing model can at any time be "improved" by new treatment data and, in this way, take into account long-term variations of certain input data that hardly can be taken into account based on subsequent treatments only.

Estimate Model Parameters Based on Selected Heats: Two models might be different in parameters only, i.e., trained with different sets of treatments, e.g., good heats vs. bad situation. The latter model can be used to

Figure 5



New models by logical connection: green = okay, red = not okay.

know whether the system is getting close to a certain pathologic case.

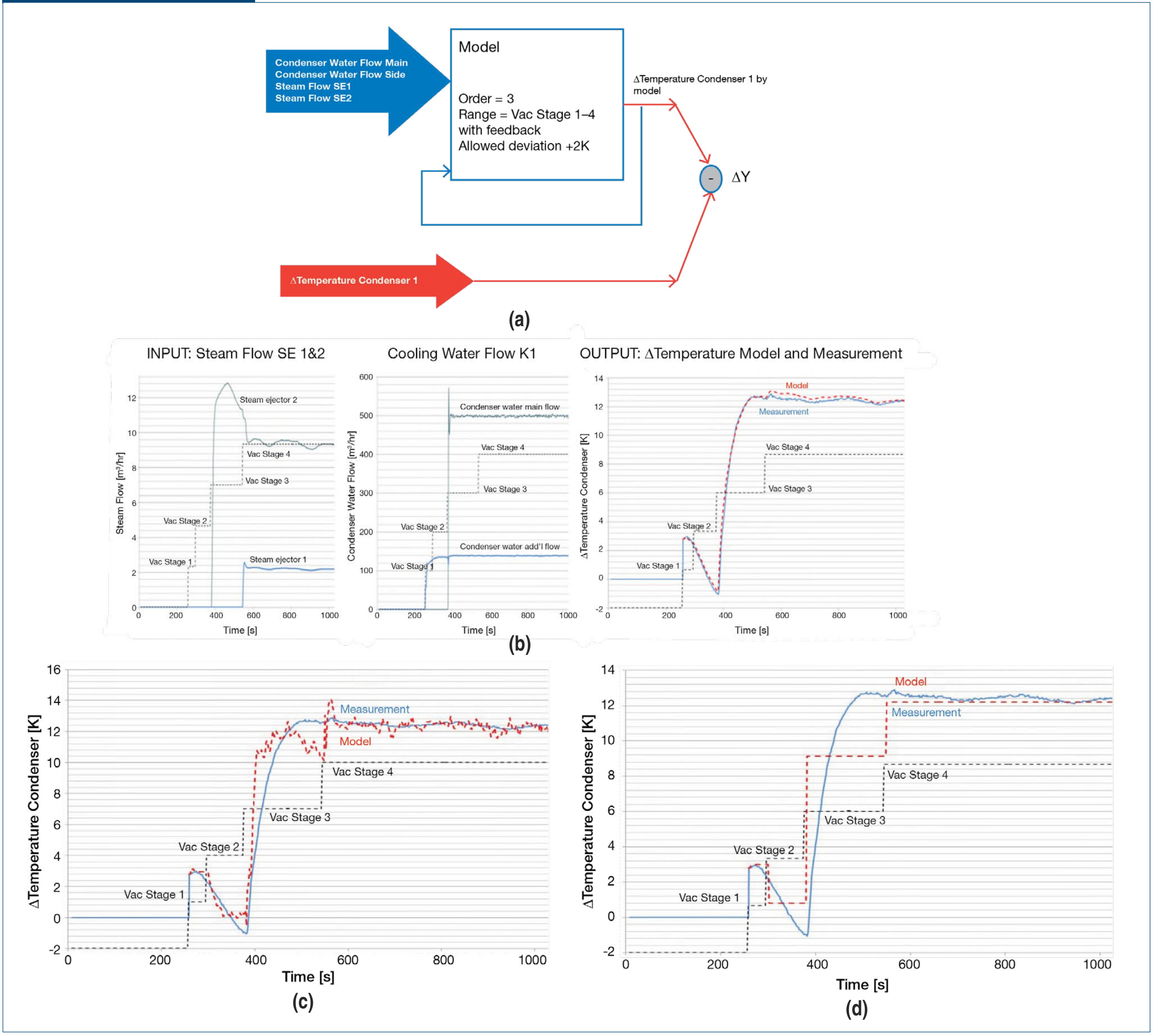
The number of parameters depends on model order and the number of input values. For example, a model of order 3 and 2 input values X_1, X_2 is described by 3 + 2 * 3 = 9 parameters. Further, the model parameters are determined individually for each vacuum stage (Table 1); therefore, in the given example, the model would have 4 * 9 = 36 parameters.

Model Variants — In the following, the effect of the basic modeling alternatives shall be demonstrated, namely:

- Model 1: Relative model with a number of input values with a plausible relation to the output
- Model 2: Absolute model – without feedback
- Model 3: Value check, without input values (just the vacuum stages 1–4).

The temperature increase ΔT of condenser cooling water during the evacuation is an important criterion for good pump performance. ΔT for each of the three condensers must not exceed a value of about 15 centigrade, a value being specific for each vacuum pump. It is only plausible that ΔT depends on the flow of cooling water. Typically there is a main flow and a lesser additional

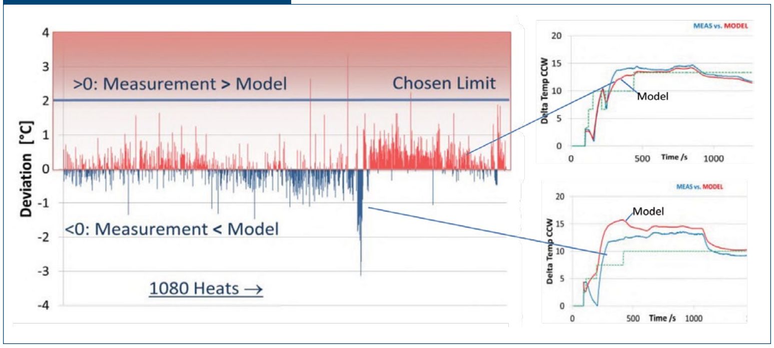
Figure 6



Model type 1 for temperature increase of cooling water in Condenser 1 (a and b); Model type 2 "absolute" for temperature increase of cooling water in Condenser 1 (c); and Model type 3 "value check" for temperature increase of cooling water in Condenser 1 (d).

flow, which are switched on depending on the vacuum stage and related steam amount. Therefore, the steam flow of the upflow steam ejectors are two more plausible quantities affecting ΔT. The left two diagrams in Fig. 6b show the input measurements of water and steam flow of the given treatment. The match between model and measurement worsens from models 1 to 3. For example: Temperature increase of condenser cooling water, condenser 1 depending on steam flows, cooling water flow.

Figure 7



Application of model to a series of 1,080 heats and resulting deviations.

Whereas in the given example, model type 1 is able to approximate the response of the cooling water temperature on surrounding conditions best; the other types seem to be less precise.

However, though type 1 provides the best approximation, the result in case of deviations is possibly less transparent; its interpretation might be difficult.

Type 2 in Fig. 6c seems to be unsuitable for the given example; still, this model type can be the preferred choice in case there is a relation of input and output values, say, of the kind y = a * x + b. Examples are consistency checks of measurements, such as the total cooling water flow vs. individual flows or inlet steam pressure vs. steam pressures after steam valves when open.

Type 3 in Fig. 6d, on the other hand, is useful for the elementary, unconditional checks whether individual values are in range. It returns per vacuum stage a constant mean value of the heats used for training the model and is a valuable reference. That means model type 3 applied to all measured values represents an initial set of models (before more sophisticated models are set up) to judge whether values more or less precisely are in range.

Model Test and "Okay" Limits — After having set up and trained a certain model, it is applied to a sequence of a greater number of historical heats in order to:

- Judge their feasibility to identify deviations.
- Determine permissible limits of under- or overshots, i.e., the red-yellow-green limits.

In Fig. 7, the deviation of 1,080 subsequent heats is shown. A negative value means the measured value, on average, is below the model-suggested one, whereas in case of a positive value the measured value is above. This is illustrated by means of the trends of the two cases (red curve = model, blue curve = actual value). In the upper one, the measured value is typically above the model value, resulting in a positive deviation, which might be critical in case of exceeding the limit value.

Using this diagram, the setting of permitted limits of the respective model can be checked. In the given example, the measured temperature increase must not increase the model value plus a chosen limit value. A lesser temperature increase would be tolerable; therefore, in this case no limit is defined for an undershot of the model temperature.

SVP Performance Monitoring

The performance of the vacuum pump is mainly characterized by:

- Shortest pump-down time.
- Final vacuum level.

The pump-down is characterized by the sequence of vacuum stages and the dwell time in the respective vacuum stages. However, the dwell time in intermediate vacuum stages 2 and 3, and thus the total pump time, can be prolonged due to metallurgical restrictions or process demands; for example, due to excessive flow of CO during decarburization or the demand to keep an elevated pressure during oxygen blowing. In the case of degassing treatments, the picture is typically clearer than for decarburization treatments, which vary much more in terms of decarburization, alloying and other metallurgical demands. That's why the pump-down time by itself is not necessarily an indicator of pump performance.

For degassing treatments, however, the distribution of pump-down duration in Fig. 8a shows that pump-down time, vacuum stage 2 from 300 to 70 mbar, is max. 22 seconds for the majority of treatments. A value greater than that is an indicator of malfunction or abnormal conditions. The prolonged duration of vacuum stage 2 is a result of insufficient steam pressure. Though the steam pressure seems to recover in the course of further pump-down, the pump-down duration is clearly prolonged. The reason is then signaled by a corresponding model supervising the steam pressure. The normal case of a steam pressure close to the model pressure is shown for comparison.

MCMS Application Software

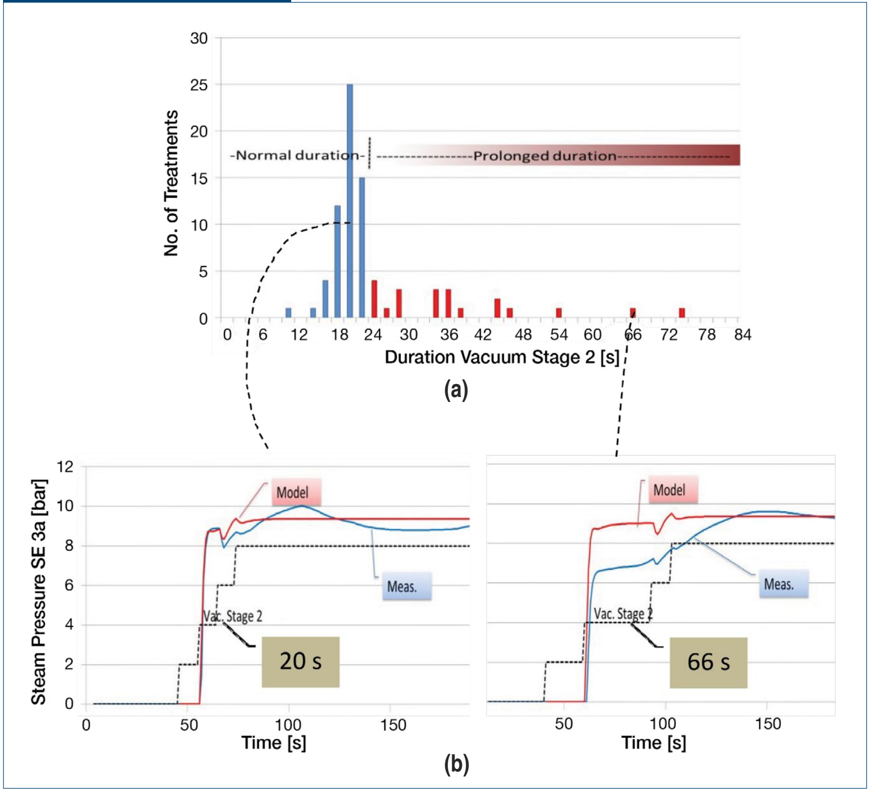
The application software cyclically feeds sampled data and derived data from PLC (via database) to a set of models.

The models, configured as described above, reside in the database with their corresponding parameters. They can be updated at any time through the database. The application software then rereads the models and continues the evaluation.

Main Features — The main features of the application software are:

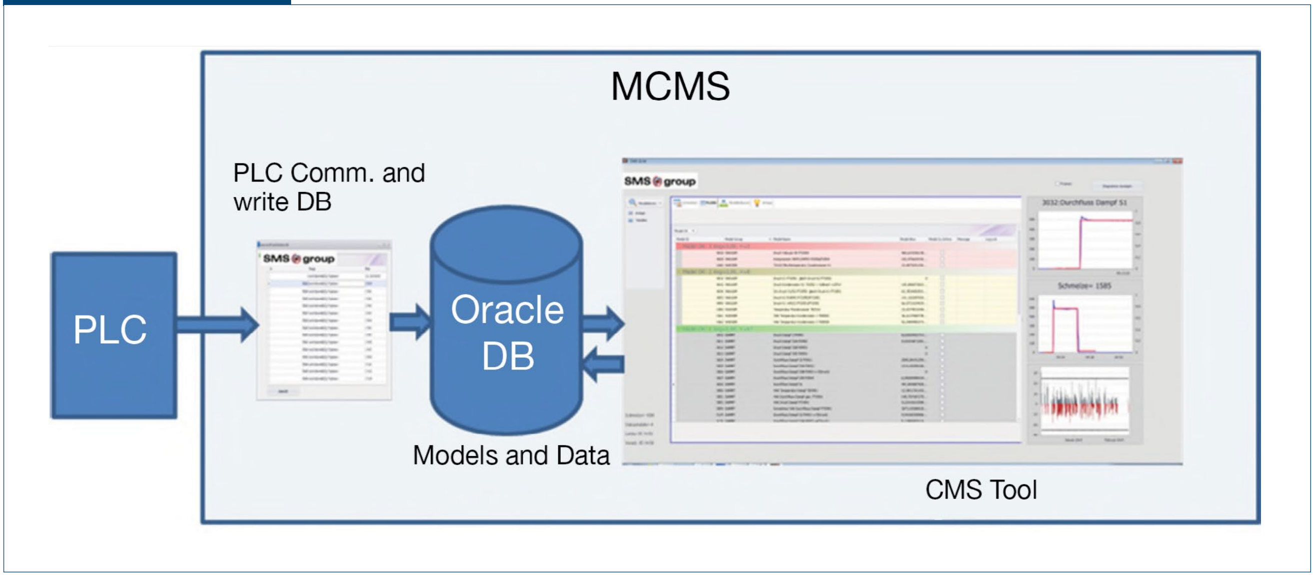
- Condition monitoring by a diverse dialog system to check the SVP status, including functional table controls, SVP mimic, trends and histograms.
- Scalability by adding, removing and updating of the "model base."

Figure 8



Distribution of pump-down duration (vacuum stage 2, degassing treatments only (a) and vacuum stage 2 prolonged due to reduced steam pressure (b).

Figure 9



MCMS connected to PLC via database.

- Learning: readjustment of models, e.g., after maintenance of the SVP.
- Many years of historical data, measurements and model data available for comparison.
- Recalculation of historical data after update of models.
- Differentiated consideration depending on the vacuum stage.

Condition Monitoring — To facilitate SVP maintenance, the maintenance staff is given information and hints as follows:

- Conditions of steam, water, vacuum profile and off-gas during SVP operation.
- Condition of SVP components, especially:
  - Motive nozzles of the steam ejectors.
  - Condensers.
  - Check valves.
  - Leakage detection.
- Plausibility of measurements.
- General performance SVP indication (pump-down behavior, end vacuum).
- Monitoring of reoccurrence of special recorded historical cases.

In Fig. 10, taken from the trial run of the application software, a model signals a deviating steam flow through steam ejector SE1. Steam through this ejector is supposed to flow in vacuum stage 4 only. The deviation is due to premature opening of the corresponding steam valve. In the plant mimic, a traffic light gauge indicates a possible malfunction. Clicking the gauge shows the related diagnostic messages and advice to the maintenance staff ("action"). In a second dialog, the trend of models and measurements reveal why the associated model responded to the problem.

Dialog System — An SVP mimic provides the main access to the system with basic functionality:

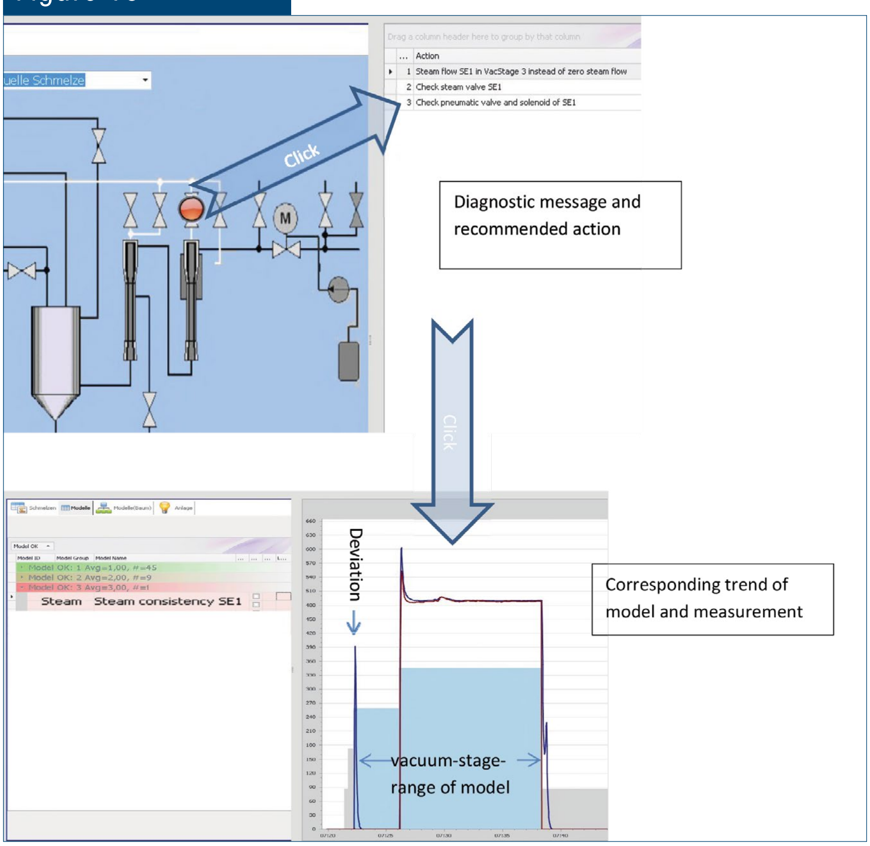
- Traffic light (red-yellow) at SVP components.
- List of diagnoses and recommended actions, both general and per non-green signal.
- View traffic light for selectable historical heats or average traffic lights of recent heats.
- View trends related to non-green signals.
- Access to detail dialogs, including:
  - Model results of current heat, previous or selected heat.
  - Model-related histogram of all heats in the database.
  - Trends model vs. actual and trends of related model inputs.
  - List of models sorted by their traffic light value.
  - List of heats with characteristic data in view of SVP performance.
  - Dynamic trends of the current heat vs. model calculation.
  - Trends of historic heats.

Conclusion

Though the SVP is a relatively complex plant, SMS Mevac's approach of a CMS system basically is simple and straightforward.

Based on additional instrumentation, a process-accompanying evaluation software provides information on the state of the vacuum pump to point out certain error conditions. On a special computer dialog, the

Figure 10



Problem signaled on the dialog.

derived information is displayed and used for preventive maintenance.

For setup, using the measured value series of "good" vacuum treatments, transfer functions are estimated. The estimated transfer function reflects as a model of the physical behavior of the system including time constants. If these models are now applied to the cyclic measurements of the current vacuum treatment, conclusions can be drawn from the difference between model and actual value. There is no need to pre-set parameters. The models self-adjust or readjust on running or selectable historical treatments. In an ongoing trial operation, it has already proven its feasibility.

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