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Feasibility study of forced cooling of a supercritical steam turbine after a shut down of a power generating unit

WOJCIECH KOSMAN[*]

Silesian University of Technology, Institute of Power Engineering
and Turbomachinery, ul. Konarskiego 18, 44-100 Gliwice, Poland

Abstract Temperature related decrease of steam turbine components is one of the main transient processes that occur during a typical long-term operation. With a natural cooling (no user interference) it takes more than 14 days before the temperature of components reaches the level that allows to open and repair a turbine. It is then reasonable to apply a forced cooling in order to decrease the time between a shut-down of a power generating unit and a beginning of a repair. This paper presents the analysis of application of a forced cooling process to supercritical steam turbines. The main problems under the investigation are the safety issues of the process and the optimization of cooling conditions. The paper describes the safety restrictions and the optimization criteria. The process is analyzed in numerical simulations conducted for various cooling conditions.

Keywords: Supercritical steam turbine; Transient process; Stresses; Optimization

Nomenclature

c – cooling air
IC – inner casing
m – mass flow rate, kg/s
R – rotor

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[*] E-mail address: wojciech.kosman@polsl.pl

OC – outer casing
T – temperature, °C
t – time, h
z – distance along the axis of the rotor, m
v – rate of temperature change, K/min
w – elongation, mm

1 Introduction

Various strategies suggested for the future simultaneously yet independently acknowledge a significant contribution of coal fired units in the generation capabilities of the electrical power [1]. Recent years brought a constant development in the field of steam turbines [2,3]. The most important is the increase of the steam parameters into the supercritical values. The increase is related to new solutions in the design of the turbines [4].

The analysis presented in this paper is a part of a larger research project that focuses on the improvement of operation of power generating units with supercritical steam turbines. The research investigates various aspects of operation including steady and transient states. The aim is to improve the flexibility of the power units. A particular problem described here is the cooling of the turbines after a shut-down of a power unit.

The temperature decrease of steam turbine components is one of the main transient processes that occur during a typical long-term operation. A natural cooling (no user interference) requires about 14 days. During that period the rate of the temperature change in the components is small and the thermal stresses are far from their allowable values. The turbine neither generates power nor may be subject to any maintenance procedures. It is then reasonable to apply a technology that forces faster decrease of the metal temperature. Application of such technology to supercritical steam turbines requires, however, a careful analysis of the whole process that would allow to determine the range of the possible increase of rate of the temperature decrease. Moreover, the analysis must also allow to verify the safety of the process and optimize its progress. The research presented in this paper involves a numerical modeling of the thermal conditions after the shut-down of a power unit and their influence on the cooling process. The range and restrictions of the forced cooling are then estimated basing on the numerical simulations.

2 Natural and forced cooling

A time progress of the natural cooling is presented in Fig. 1. The graph shows the temperature of the high pressure inner casing after the shut down. The measurement data were gathered for a supercritical steam turbine with the live steam temperature at the level of 560 °C. The corresponding rate of the temperature decrease was around 0.3 K/min in the first hour of the cooling and less than 0.1 K/min thereafter. This rate of the temperature decrease is small when compared to the allowable values at 2 K/min. It means that there is a large room for improvement of the pace of cooling. Also the period of 14 days is very often unacceptable. A failure may for example prevent a long cooling process if the turbine rotor is damaged and cannot be hold in low speed rotations.

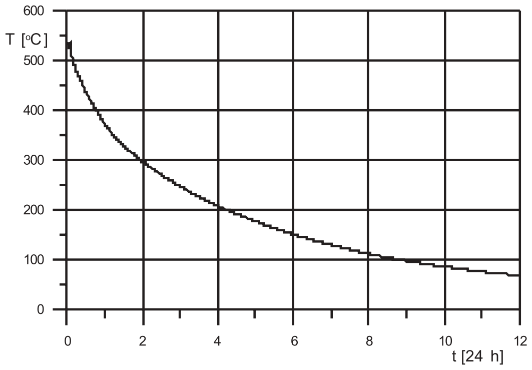

Figure 1. Temperature of the high pressure inner casing after a shut down.

The cooling time may be shortened through the use of various methods. The most popular ones are listed below.

I **Shut down with a sliding parameters**
During a shut down a turbine is fed with a live steam at lower pressure and temperature. This is a type of operation under "sliding conditions". In effect components of the turbine are exposed to the steam at lower temperature and their temperature decreases. However operation under the sliding conditions is economically ineffective. Also the minimal temperature of the components is quite high since temperature of the steam must be kept above a certain level.

II **External steam cooling**
Steam at low temperature and pressure may be delivered to a turbine

right after shut down from an external source. The steam then flows through the system of rotors and stators and lowers temperature of the components. In this case temperature of steam may be lower than in the case of a shut down under sliding parameters.

III **Air cooling**
Right after the valves are closed and the live steam flow is stopped the air is supplied to a turbine. Air may either be compressed and delivered to a turbine through a compressor or a compressor may create a partial vacuum in a turbine. In either case the minimum temperature of the air that flows into the turbine is equal to the ambient temperature. The temperature is much lower than in the previous two methods of the forced cooling and the forced cooling is very effective. This cooling process is very flexible in the sense that it may start immediately after a shut down and may proceed until the temperature of the components reaches the desirable level.

Of the methods compared the air cooling is the method that may be applied in a wide range of temperature of the components. It also allows to adjust the cooling conditions in order to obtain desired rate of the temperature decrease. Therefore the air cooling is under the further investigation here.

3 Assessment of the cooling process

Application of air cooling to supercritical steam turbines after a shut down requires the analysis of following issues:

- safety,
- effectiveness,
- selection of the cooling conditions (parameters of the air flow).

Among these issues the main problem is safety of the cooling process. It is related to two aspects, namely stresses and elongations. The first aspect corresponds to the thermal stresses only. Pressure of the air delivered to a turbine is just slightly above the atmospheric level, thus it is far lower than the live steam pressure in standard operation. The cooling process is conducted also with small rotational speed (about 50 min^{-1}). The mechanical stresses may then be neglected leaving only thermal stresses that result from the changes in the temperature field in the components. The second aspect of the safety is related to the elongations. The clearances between the rotor and the stationary components must be kept within allowable limits.

The progress of the cooling process in traditional, subcritical steam turbines is usually monitored through the following measurements:

- inner casing temperature,
- outer casing temperature,
- outer casing absolute elongation,
- rotor absolute elongation.

The measurements in the list above do not allow to determine uniquely the thermal state of a turbine. There is neither information about temperature of the rotor nor about the elongation of an inner casing. Analysis of the air cooling in supercritical steam turbines should be useful in estimation of temperature and elongations in the main components.

Effectiveness of the cooling process is related to the time that is necessary to lower temperature of the components to a desirable level. In order to assess the cooling process the analysis described here applies the time t_{100} as a measure. This is a period between the beginning of cooling and the moment when temperature of the component falls below 100 °C. The time t_{100} is related to the mean cooling rate of temperature decrease v_{100} as shown in Fig. 2.

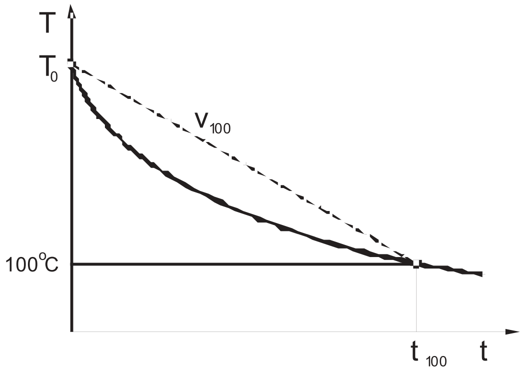

Figure 2. Time of the cooling process (t_{100}) and mean rate of temperature decrease (v_{100}).

The third problem that arises when applying cooling to supercritical steam turbines is the selection of appropriate cooling conditions. The main issue here is the amount of air that should be delivered to a turbine. The flow may be adjusted during the process according to the thermal behavior of the turbine components. Another issue is the flow direction in the turbine which is discussed in the next section of the paper.

4 Cooling flows

The cooling air may be supplied at various locations of the turbine. The air inlet may be located in the live steam pipes, extraction pipes or steam outlet pipes. Due to the relatively small amount of air (when compared to the amount of steam during the operation in design conditions) and the heat transfer between the coolant and the components the temperature of the air increases along the turbine. In the most natural arrangement the cooling air flows through the turbine in the same direction as the steam during a standard operation (Fig. 3). The air flow may also be reversed: from the turbine outlet to the turbine inlet. This results in more uniform distribution of the air-metal temperature difference since the air temperature increases before it reaches the hottest parts in the area of the live steam inlet.

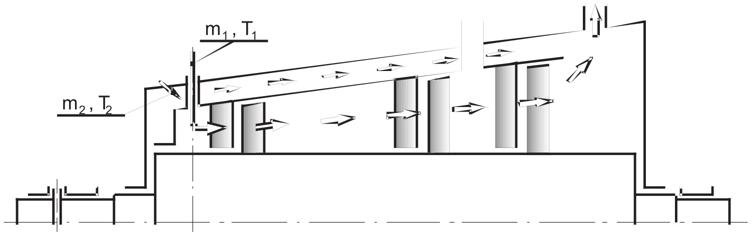

Figure 3. Air flow with two streams.

The cooling air flows through a turbine in two parallel passages that include the following areas:

1) the rotor-stator system of blades (the steam path): the air of the initial temperature T_1 and the mass flow rate m_1 flows between the rotor and the inner casing,
2) the area located between the inner and the outer casing: the initial temperature of the air is T_2 while the flow rate is m_2.

The design shown in Fig. 3 includes two separate streams. The amount of the air in the streams may be different. It is also possible to arrange the flow with a single stream. In the design shown in Fig. 4 the cooling air flows through the steam path first and then is forced into the area between the casings. Temperature of the air entering the second passage (T_2 in Fig. 4) is higher than the air temperature at the inlet (T_1). The value of T_2 depends on the cooling conditions in the first passage (e.g. amount of the air and the temperature of the components).

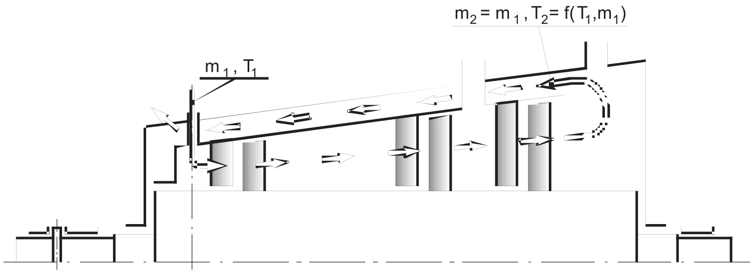

Figure 4. Air flow with a single stream.

Apart from the two main streams described above the cooling air also flows through the seals in the inlet and outlet part of the turbine. The analysis must also include these flows since they cool large surfaces of the main components of the turbine.

5 Numerical model

According to the discussion given in the previous sections the analysis of the cooling must be conducted in various conditions. The assessment includes the determination of thermal stresses in the cooled components, their elongations (including unmeasured rotor to inner casing elongation) and the total time of the process (t_{100}). The analysis described here employs a numerical model of main components and air flows in a supercritical steam turbine as shown in Fig. 5.

The numerical model includes five temperature fields (see Fig. 5) gathered in the following list:

- rotor $T_R(r,z)$,
- inner casing $T_{IC}(r,z)$,
- outer casing $T_{OC}(r,z)$,
- air flow through the steam path $T_{c1}(z)$,
- air flow between the casings $T_{c2}(z)$.

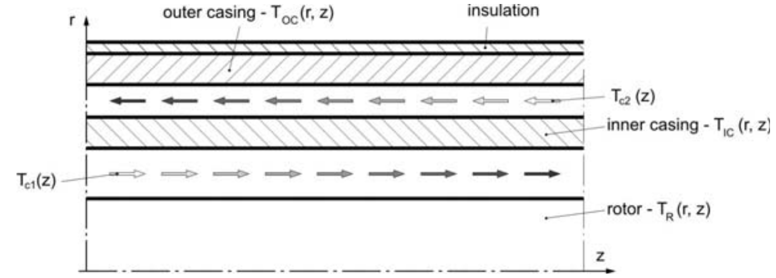

Figure 5. Thermal model of the coupled temperature fields.

Due to the nature of the cooling process the temperature fields in the components and the flows are coupled. The components are modeled as axisymmetrical solids, while the streams are treated as one-dimensional flows in a ducts with a heat transfer through the duct walls. The flows are modeled only to the extend that is necessary to formulate boundary conditions for the thermal analysis of the components. A detailed description of the model is given in [5]. The advantage of the model is a relatively small computational time, which allows a large number of simulations of the transient problem.

The temperature distribution as well as stresses and elongations were determined in a finite element module. The geometry of the components under the investigations is presented in Fig. 6. The meshes applied in the computations are also shown.

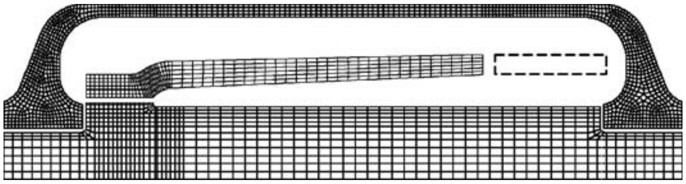

Figure 6. Numerical model of the main components of a supercritical steam turbine.

The component drawn in a dashed line corresponds to the stator blades in the rear part of the turbine (not attached to the inner casing). The analysis of stresses and elongations does not include these components. The heat transfer however between the stator and the cooling air is included in the analysis of the coupled thermal fields. The change of air temperature due to the stator cooling is significant.

6 Initial conditions

Simulations of the cooling process start at the moment of shut down, immediately after the live steam valves are closed and the pressure in the turbine trips almost to the ambient level. It is assumed here that the initial distribution of temperature in the components is the same as in the operation under design conditions. This is the worst-case scenario with the highest values of the metal temperature at the beginning of the cooling process. During the shut down live steam temperature is kept at a high level until the valves are closed (the pressure decreases earlier). However in practice it is often observed that the live steam temperature also decreases earlier and the cooling process starts before the air is delivered to a turbine.

7 Forced cooling — single flow

The analysis of the forced cooling involved a number of cases with various cooling conditions. The first case is a forced cooling with a single flow. The arrangement of the stream is shown in Fig. 4. The results of the numerical calculations are presented in Fig. 7.

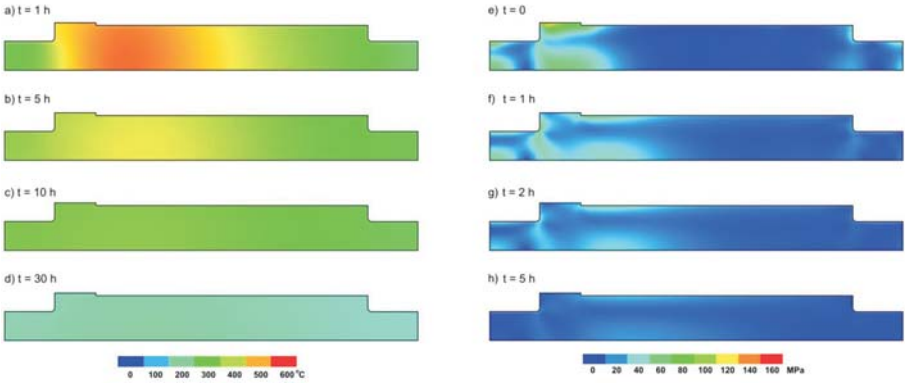

Figure 7. Temperature (a–d) and stress (e–h) distribution in a rotor during a cooling with a single air stream.

Figure 7 shows temperature and stress fields in the rotor of the investigated turbine in chosen moments of the cooling process. Time is measured from the beginning of the process. It may be observed that the temperature becomes uniform rather early. The stresses follow with the most intense changes in the first couple of hours.

Figure 8 presents a comparison between the cooling from Fig. 4 and the reversed flow: the air also flows in a single stream but in the opposite direction to the flow shown in Fig. 4. The graphs correspond to the change of temperature in the locations of the rotor (Fig. 8a) and the inner casing (Fig. 8b) where temperature reaches the maximal values. The two cases differ in the time required for the cooling process (t_{100}). The cooling conducted according to the case no. 1 requires about 8 h shorter period.

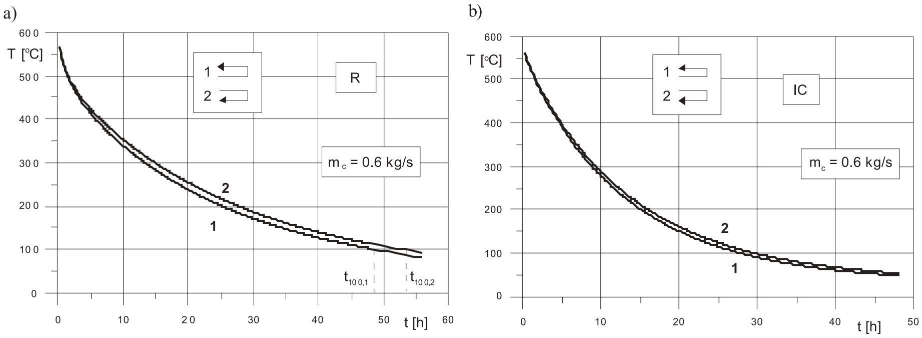

Figure 8. Temperature of the rotor (a) and the inner casing (b) in a single stream cooling: flow according to Fig. 4. (stream 1), and in the opposite direction (stream 2).

The amount of the cooling air is subject to the adjustment. The numerical model may be used to simulate the effects of the cooling with various mass flow rates. Appropriate graphs are shown in Fig. 9 for the cooling conducted with a single stream reversed to the flow in Fig. 4. The lines in Fig. 9a correspond to the cooling with two different mass flow rates.

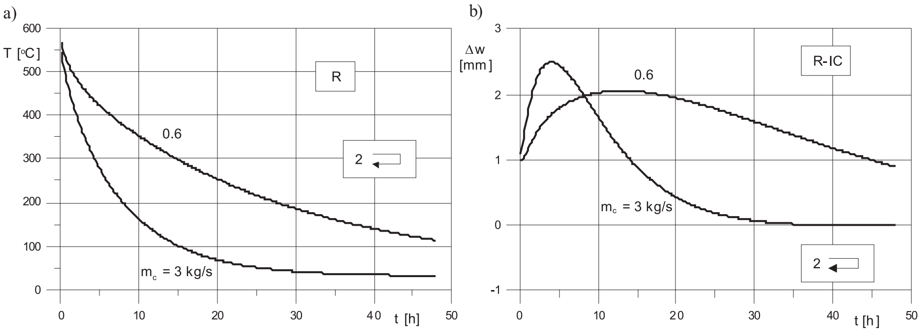

Figure 9. Single flow with various amount of air: temperature (a) and relative elongations (b).

Higher flow rate leads to shorter periods of cooling. The rate of temperature decrease is much higher — the line that corresponds to the temperature progress is much steeper for the higher m_c. The drawback is a higher value of relative elongations between the rotor and the inner casing (Fig. 9b). This violates the process safety.

8 Forced cooling — double flow

The results of simulations for cooling with a double flow are shown in Fig. 10. In the case no. 3 air flows in two separate streams as shown in Fig. 3, while in the case no. 4 the streams flow in the opposite directions (from the turbine outlet to the inlet). In order to compare various cooling conditions Fig. 10a includes also the line that corresponds to the single flow cooling (case no. 2 discussed in the previous section).

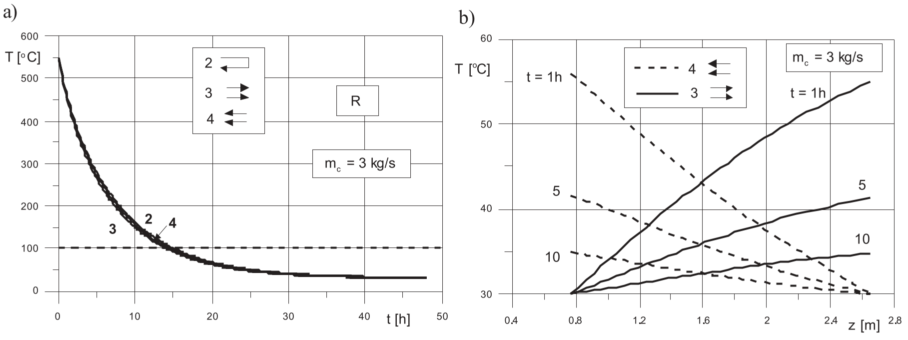

Figure 10. Rotor (a) and cooling air (b) temperature for a double flow cooling.

It may be found that the differences between the lines in Fig. 10a are small. The total time of cooling (t_{100}) is very similar with the differences reaching no more than one hour. Small differences result from a relatively high amount of the cooling air. In very early stages of cooling the air temperature along the turbine becomes uniform and similar in both cases nos. 3 and 4. This is shown in Fig. 10b. The lines in the figure correspond to the distribution of the air temperature along the turbine. The horizontal axis in the figure is a distance measured along the rotor axis. It may be noticed that in the first hour of the cooling there is a high difference of the air temperature at the turbine inlet and the outlet. However as the cooling proceeds the lines representing air temperature become almost horizontal in both cases and the temperature difference is about 5 K. This means that cooling conditions are in fact almost the same.

9 Optimization

All the results presented so far were obtained from simulations for mass flow rates that were constant over the time of the cooling process. These simulations were performed in order to determine the possible range of the cooling process. The final step is a selection of the specific cooling conditions for a particular turbine.

The best approach towards the adjustment of the cooling condition is the change of air mass flow rate. The influence of the flow direction on the temperature, stresses and elongations is small for higher flow rates and the higher flow rates are required to obtain short cooling periods. As mentioned before, optimization of the process must respect the cooling restrictions. The results presented in the following figures were obtained using a criterion of the allowable rate of the temperature decrease, which is related to the allowable level of stresses. The optimization procedure assumed that the allowable rate of the temperature change is 1 K/min for the material of main components of the turbine. The air flow configuration was the same as in the case no. 3 (see Fig. 3). This time however the air flow was adjusted during the cooling.

It was assumed that the adjustment is performed once per hour in the first stage of the cooling process. The air flows are changed so the rate of the temperature decrease is close to 1 K/min. This is shown in Fig. 11a. The simulations showed that the best approach is to first change the air flow in the stream that flows through the rotor-stator system only. Then, in the seventh hour the second stream that flows between the casings is also adjusted. This optimization results in the change of the maximal temperature of the main components according to the lines shown in Fig. 11b.

In the presented optimization the adjustment of the air flow is applied in step-changes in constant periods. This is a very comfortable situation for the user because once the cooling procedure is adapted no control measurements are necessary — the measurements are required for the monitoring purposes only. It is also possible to conduct the cooling with the changes of the air flow performed in shorter periods, e.g. every minute or even shorter. Such a procedure would require a control system that would drive the air valves.

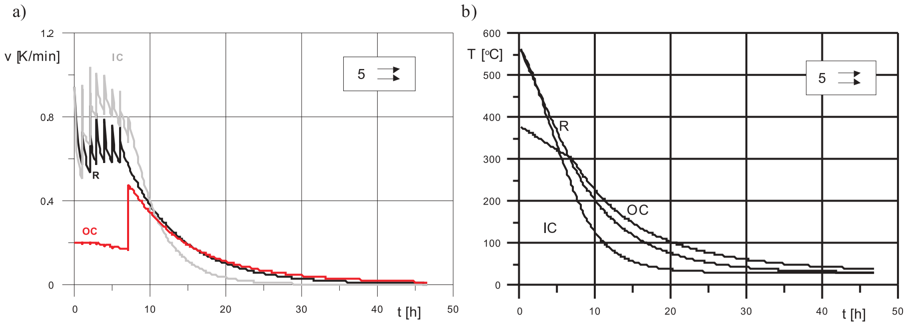

Figure 11. Rate of the temperature change (a) and the temperature of the main components (b) during an optimized cooling.

10 Summary

The simulations performed within the research presented in this paper allowed to determine the possible range of the cooling conditions after a power unit shut down. The methodology described here may be applied to any supercritical steam turbine. The methodology provides safe procedures that may be applied even without a control system. Safety is the major restriction applied in the selection of the appropriate cooling conditions. Compare for example relative elongations between the rotor and the inner casing for the optimized cooling shown in Fig. 12 with the elongations in Fig. 9c. The graph in Fig. 12 proves that the relative elongations are smaller for the optimized cooling than for the processes conducted with constant flows.

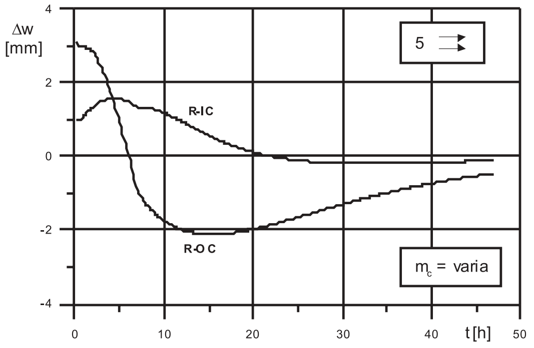

Figure 12. Relative elongations during the optimized cooling.

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