Proceedings of the 15th International Heat Transfer Conference, IHTC-15
August 10-15, 2014, Kyoto, Japan

IHTC15-8632

# ENERGY EFFICIENT COOLING OF SWITCH CABINETS USING OPTIMIZED INTERNAL SETTINGS

**W HEIDEMANN, C STAUB, K SPINDLER**

Institute of Thermodynamics and Thermal Engineering, University of Stuttgart, Germany

## ABSTRACT

The miniaturization progressing of electronic components - used in switch cabinets for manufacturing - increases the packaging density as well as the volumetric dissipation power of the electrical components. As a result, high air temperatures inside the switch cabinets, an overheating and, with that, a reduction in the component life time may result. For this reason, switch cabinets must be cooled actively very often. The commercial CFD code FloTHERM is used to obtain the influence of the packing density of the electrical components, the geometry of the wiring system and the inner air flow on the temperature and the velocity distribution inside a switch cabinet of given size. Based on CFD calculations, measures for optimizing the internal setting of switch cabinets are presented in order to be able to use cooling capacity provided by active cooling devices (e.g. air/air heat exchangers, air-conditioning units) as energy efficiently as possible for the avoidance of hotspot areas (areas of a high inside air temperature). For the validation of the CFD model, as well as the verification of the suggested optimizations, experimental data are used. The experimental data are obtained from measurements of temperatures and flow velocities, carried out at a test equipment for switch cabinets in the laboratory. To reproduce the thermal situation inside the tested switch cabinet, empty housings of electronic components are fitted with resistance heaters and installed in the switch cabinet. By a single pulse-width modulated voltage, applied to each resistance heater, a variable distributed overall dissipation power is adjustable. Different steady-state operating conditions of the switch cabinet with natural and forced convection with and without cooled air are investigated. Theoretical results for optimized internal settings of switch cabinets show potential for the conservation of cooling energy up to 23 % compared to the not optimized initial state.

**KEY WORDS:** Electronic equipment cooling, Energy efficiency, Thermal management

## 1. INTRODUCTION

The dimensioning of the air conditioning of switch cabinets is carried out predominantly with simple macrostructure models in the industrial practice up to today, see Styppa [1]. The steady state caloric mean temperature of the inside air is described as a function of the component dissipation power for different air conditioning techniques (e.g. heat exchanger, cooling unit). Basis for the calculation of the inside air temperature is a steady state energy balance under consideration of basic heat transfer mechanisms like conduction, mixed convection and radiation.

Fig. 1.1 shows exemplarily a characteristic diagram as a result of this simple one-dimensional treatment for a switch cabinet of predefined geometry. The areas coloured differently in Fig. 1.1 are assigned to certain air conditioning techniques. A crossing through these areas at a constant air temperature in the direction of increasing dissipation power requires a rise of the energy demand for the air conditioning of the switch cabinet. The maximum air temperatures result, if no active cooling (free convection) is used. This operation case represents the upper limit of the characteristic diagram.

*Corresponding Author: heidemann@itw.uni-stuttgart.de

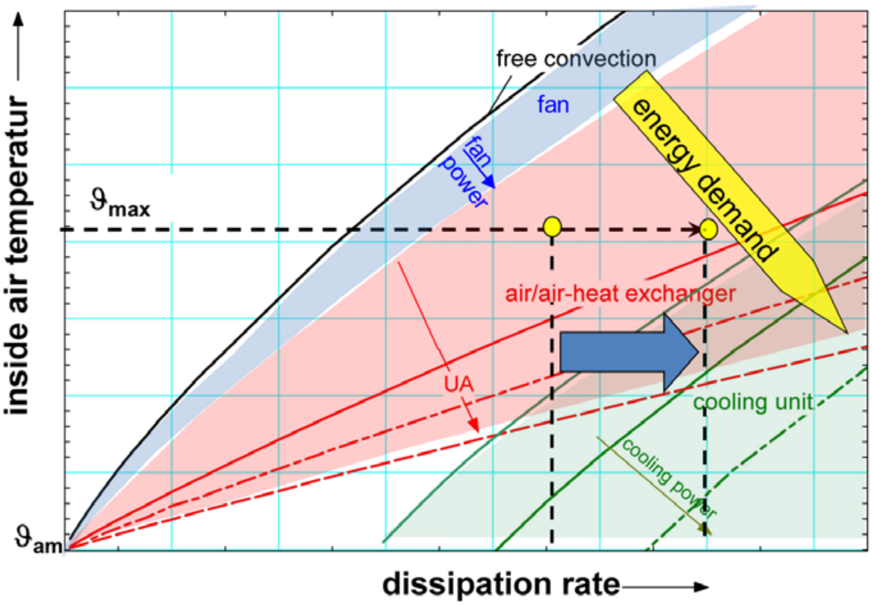


**Fig. 1.1** Characteristic diagram as a result of a macrostructure model.

The assignability of the homogeneous caloric air temperature on real thermal conditions in switch cabinets is restricted. Tierny and Koczkur [2] showed that the assumption of an average inside temperature distorts the calculation of the heat transport in switch cabinets. Real temperature distributions in the air volume of switch cabinets are not homogeneous, but minted rather multidimensionally.

The real temperature conditions are influenced by the air flow inside the switch cabinet, the wiring system, the dissipation power and its distribution, the component arrangement, as well as, by the site of the switch cabinet. Du and others [3] showed that with the arrangements of the components the convective heat transfer and, with that, the component cooling is influenced in flow channels. Bessaih and Kadja [4] examined numerically the influence of the component distance in flow channels on the component cooling. Felczak and others [5] introduced investigations for the optimal arrangement of electronic components.

Air zones with considerably higher local temperatures than the theoretical value of the caloric air temperature (hot spots) arise from a narrow neighbourhood of components of increased surface temperature and/or flow dead man areas inside the control cubicle. The thermally most highly loaded component must get air-conditioned sufficiently in order to make sure the functionality of the switch cabinet. For an energy efficient operation of switch cabinets, it is therefore necessary to ensure an efficient appropriation and tailored distribution of cooling heat flow. The distribution of cooling heat flow has to be carried out so that no hot spots arise or the thermal expression of the hot spots is at least decreased.

## 2. EQUIPMENT

A switch cabinet from a manufacturing process of the automobile industry was chosen (cf. Fig. 2.1) to examine the thermal situation and operating behaviour. By means of in situ temperature measurements, using 40 measuring points at the inside and the outside of the switch cabinet, the total dissipation rate of the electronic components was measured to 700 W during a steady state operation mode. The characteristics of the industry switch cabinet are listed in Table 1.

In order to perform detailed temperature and velocity field analysis, it is necessary to increase the number of measurement points compared to the number of sensors used for the in situ measurement campaign. For this reason, a switch cabinet test rig was built up in the laboratory. The test rig allows the measuring of industry switch cabinets in original size with up to 85 Pt100 resistance thermometers, as well as, numerous anemometers for the selective flow velocity measuring. The measurement of local flow velocities is required, e.g., for the determination of the volumetric flow in the entry and the outlet of active air conditioning devices (cooling units, heat exchangers). For the laboratory investigations, no real electronic components were operated under load in the examined switch cabinet. Rather high load heating resistances were installed into perforated empty metal or plastic castings (virtual components) to reproduce the real operation situation (see Fig. 2.3). Thus, a defined heat flow rate can be adjusted by a pulse-width modulated 24 V direct voltage supply for the plugged heating resistance of every virtual component. The heat flow rate corresponds to the dissipation power appearing in reality. In total up to 160 virtual components can be controlled by SPC. The concept of the virtual components with size of real electrical components permits a realistic reproduction of the arrangement of components, of the dissipation rate and its distribution in the switch cabinet, see Fig. 2.2. The test rig is operated in a climatic chamber. Thus, the consideration of ambient temperatures in the range of 0 °C to 40 °C is possible at the experimental examinations.

**Table 1** Spezifications of the in situ switch cabinet.

| | | | |
|---|---|---|---|
| Height | 2000 mm | wiring system | Lütze LSC |
| Width | 1000 mm | Conditioning | heat exchanger at rear wall (U×A=62 W/K) |
| Depth | 600 mm | total dissipation rate | 700 W |

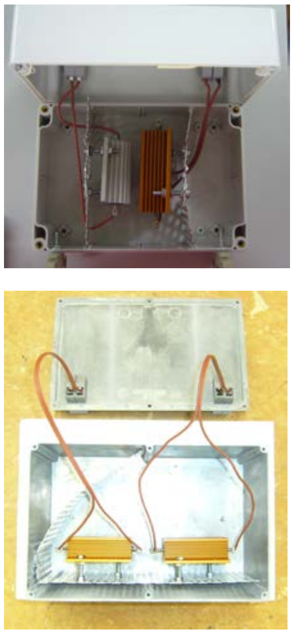

**Fig. 2.1** In situ switch cabinet. **Fig. 2.2** Experimental setup. **Fig. 2.3** Virtual component.

## 3. MODEL, COMPUTATION AND VERIFICATION

Fig. 3.1 shows a simplified sketch of the investigated switch cabinet (with e.g. air conditioning device on the top) in which the outer walls are not depicted for reasons of clearness. The position of the electronic components (grey), mounted on LSC wiring system (brown), as well as the local dissipation rate of each component is comparable to the in situ switch cabinet (see Fig. 2.1). A steady state operation mode of the switch cabinet is assumed. The locally dissipated energy of every component i (i= 1, 2, …, 24) is given in Table 2 in proportion to the total dissipated energy of the whole switch cabinet. The energy dissipated inside each single (solid) component is modelled as volumetric heat source. The dissipated energy of the components is transferred to the internal air and the surrounding walls by mixed convection and heat radiation. At the outside of the detached switch cabinet, heat radiation and free convection occurs to the ambiance. For the modelling of the interaction between switch cabinet and the ambiance, a uniformly distributed finite air volume is arranged around the side walls and the top of the switch cabinet. Besides the domain of switch cabinet, this surrounding volume of the ambiance is resolved by a numerical grid. A constant ambient pressure is assumed as boundary condition for the volume outside of the switch cabinet. In addition, a constant ambient temperature serves as infrared downward radiation temperature. View factors, used for the radiative heat flux calculation, are determined applying the Monte Carlo Method.

Active air conditioning devices mounted at top, back, front or side position of the switch cabinet, are described and considered (a) by a cooling rate and the volumetric flow at the outlet in case of a cooler unit and (b) by the overall heat transfer coefficient times area (U×A) and the volumetric flow at the outlet in case of a heat exchanger. If wiring must be taken into account, it is modelled as porous media, which is distributed over a finite volume. Two possibilities for the cable management are depicted in Fig. 3.2. The flow resistance appearing due to wiring, results in a pressure loss per meter length, which is modeled with the approach

$$\frac{\Delta p}{L} = \frac{\rho \cdot u^2}{2}\left[\frac{\mathrm{A}}{\mathrm{Re}} + \frac{\mathrm{B}}{\mathrm{Re}^{0,1}}\right]. \tag{1}$$

$\mathrm{Re} = d_{hydr} \cdot u / \nu$ represents the Reynolds number with $u$ as the undisturbed flow velocity at the entrance of the porous media. The cable diameter is used as characteristic length $d_{hydr}$ . The coefficients A and B are fixed as

$$\mathrm{A} = \frac{320\left(1-\psi\right)^2}{\psi^3 d_{hydr}}, \qquad \mathrm{B} = \frac{6{,}2\left(1-\psi\right)^{1,1}}{\psi^3 d_{hydr}}. \tag{2}$$

Equations (1) and (2) allow the description of the flow resistance in analogy to the correlation of Brauer [6], [7].

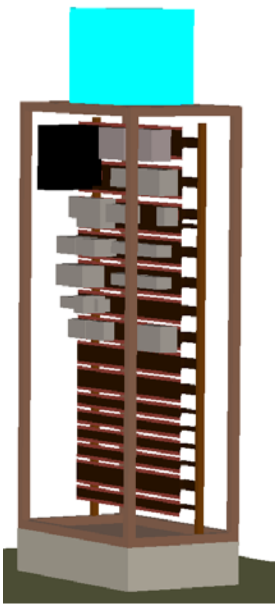

**Fig. 3.1** Geometry and internal structure of switch cabinet with LSC system and cooling unit on top.

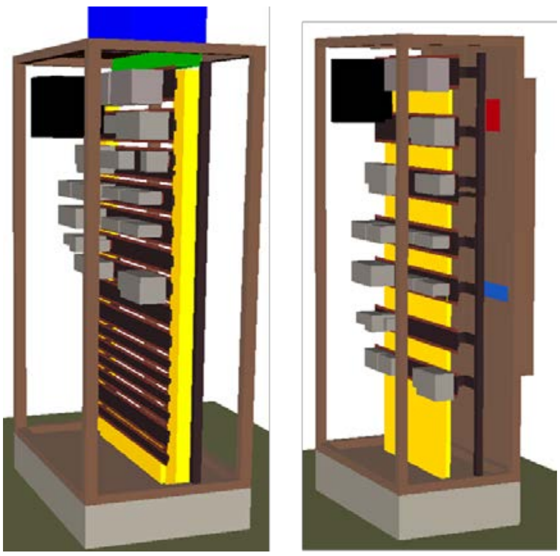

**Fig. 3.2** Cable management (yellow).

Legend to Table 2: Component numbering.

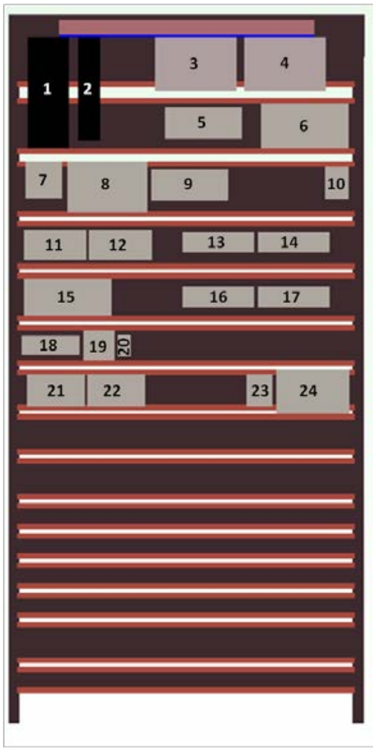


**Table 2** Relative dissipation rate of components.

| component no. | relative dissipation rate $\dot{Q}_{diss,i}/\dot{Q}_{total}$ [%] |
|---|---|
| i = 1 | 5,7 |
| 2 | 5.7 |
| 3 | 17,1 |
| 4 | 17,1 |
| 5 | 3,3 |
| 6 | 5,1 |
| 7 | 1,7 |
| 8 | 4,3 |
| 9 | 3,3 |
| 10 | 1,1 |
| 11 | 5,7 |
| 12 | 3,7 |
| 13 | 3,7 |
| 14 | 3,7 |
| 15 | 5,7 |
| 16 | 1,7 |
| 17 | 0,8 |
| 18 | 1,6 |
| 19 | 1,8 |
| 20 | 1,8 |
| 21 | 0,8 |
| 22 | 0,8 |
| 23 | 2,1 |
| 24 | 1,7 |

The governing equations for mass, momentum and energy conservation are solved numerically by using the Cartesian finite-volume program FloTHERM. Features and advantages of this commercial program are discussed by Tucker [8] and Yang [9]. A linear solver, based on the conjugate gradient method, solves the equation system in a segregated manner. In the course of this a multigrid technique is applied. For the pressure-velocity coupling a variant of the SIMPLEST algorithm is applied with stable, numerically diffusive, first order upwinding as a convective term treatment. To model the turbulence the LVEL k-ε model is used. For the near wall treatment of the flow the well-established ‘log-law‘ is applied. The meshing is automatic and delivers structured Cartesian grids containing 1.000.000 to 3.000.000 volume elements for the considered switch cabinet configurations. All 3D volume elements applied for the mesh scheme are hexahedral. The material properties of solids are constant and the properties of matter of air are assumed depending on temperature.

The numerical scheme has been validated using experimental data of two different operating modes for a switch cabinet of given size (see Fig. 2.2). For this purpose simulated temperatures at well known (sensor) positions inside the switch cabinet were compared with temperature measurements. The following two operating modes have been investigated:

- Test case 1 (see Fig. 3.3): The switch cabinet with a total dissipation rate of 501 W is operated without any active cooling device (free convection). The ambience temperature amounts to 25 °C.
- Test case 2 (see Fig. 3.4): The switch cabinet with a total dissipation rate of 700 W is operated with an air to air heat exchanger. The heat exchanger has a total heat transfer rate of 62 W/K. Local velocity measurements are used to determine the volumetric flow at the outlet of the cold air. The volumetric flow amounts to 350 $m^3$/h for the present installation situation. The ambient temperature is 25 °C.

The comparison of measured and simulated temperatures at given sensor positions (see Fig. 3.3 for test case 1 and Fig. 3.4 for test case 2) shows an agreement predominantly within 1,5 K. Locally bigger divergences between measurement and calculation (e.g. at sensor position 135 and 136 for test case 2) could be reduced by model adaptations like the consideration of wiring. For that purpose, a porous medium with a porosity of 50 % was considered in the area behind the components (see Fig. 3.2, right sketch ).

The sensor numbers denote positions in the air volume inside of the switch cabinet as follows: 115 – 124 in front of the components, 125 – 137 behind the LSC wiring system, sensors 135 and 136 above the LSC wiring system and sensors 137 and 138 below the LSC wiring system.

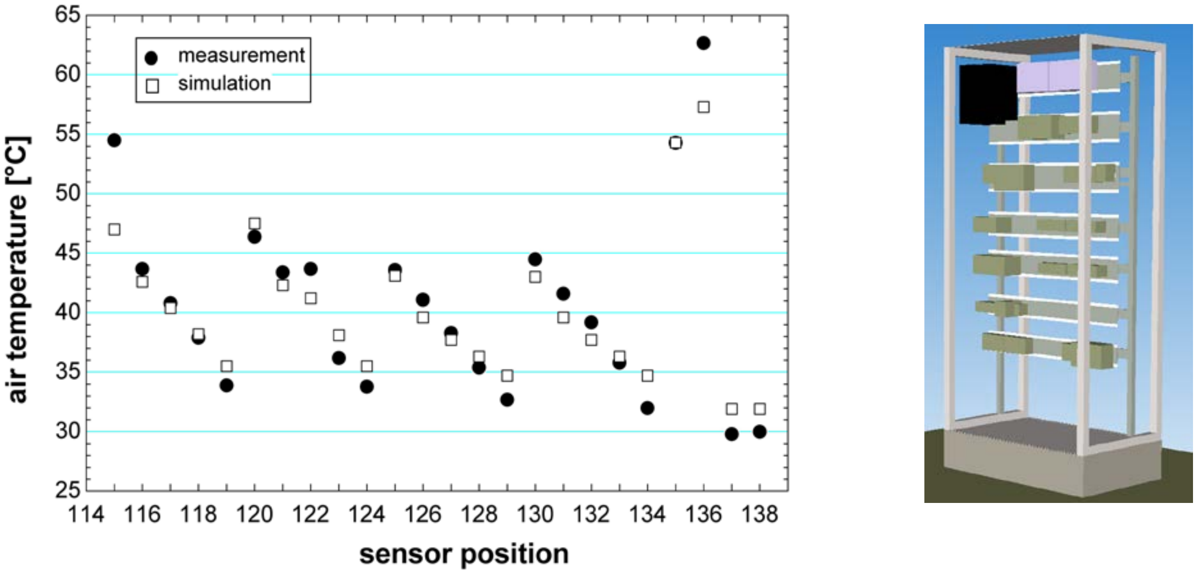


**Fig. 3.3** Test case 1 (free convection), left: comparison of measured and simulated temperatures, right: structure of the simulated switch cabinet.

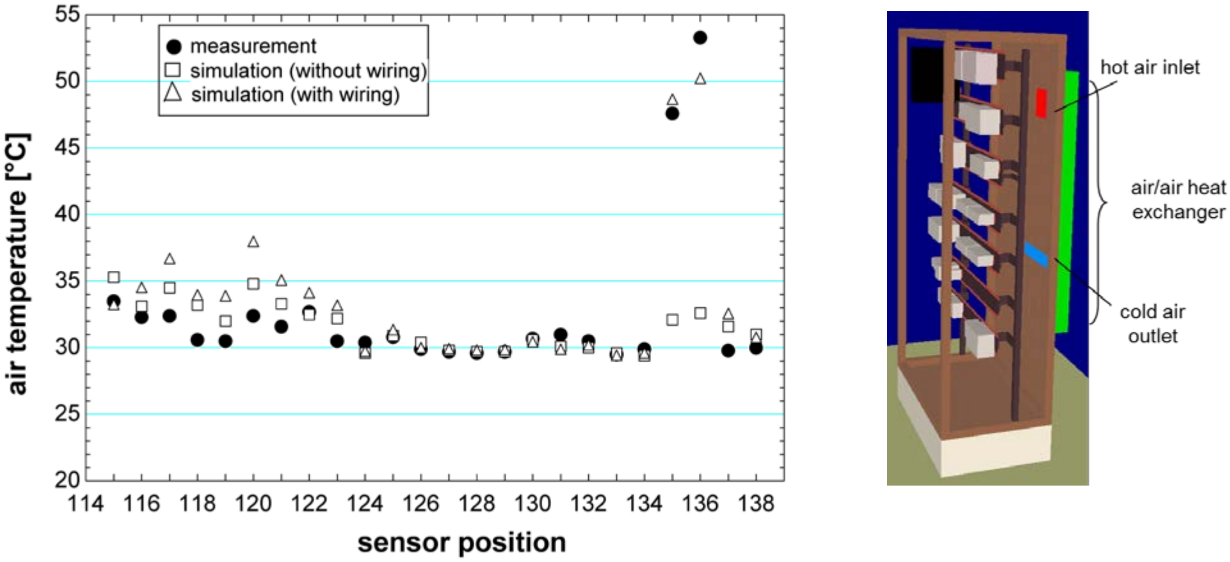


**Fig 3.4** Test case 2 (switch cabinet operating with an air/air heat exchanger), left: comparison of measured and simulated temperatures with and without wiring, right: structure of the simulated switch cabinet.

# 4. RESULTS AND DISCUSSION

Internal settings of switch cabinets have been investigated considering different operating modes of practical interest, which are listed in Table 3. The different volumetric flow rates of the fans considered for the different modes of operation (see Table 3) have been ascertained by local velocity measurements in the laboratory for the particular installation situations.

Mode 1 represents a configuration to investigate the upper limits of dissipation rate and/or ambient temperature for switch cabinet operations without active cooling devices. Only a simple fan is considered inside the switch cabinet, which generates a circulation of the inner air for the avoidance of dead zones. No air exchange occurs from the inside to the outside of the switch cabinet. Active cooling devices, mounted at different positions of the switch cabinet, are object of the investigation of the operational modes 2 - 4.

**Table 3** Modes of operation used for switch cabinet optimization.

| Mode | Description | Parameters |
|---|---|---|
| 1 | recirculated-air operation with fan | Volume flow of fan: 420 $m^3$/h, ambient temperature: 35 °C, dissipation rate: 790 W |
| 2 | Air/air heat exchanger at rear side | U×A= 62 W/K, volume flow of fan: 350 $m^3$/h, ambient temperature: 25 °C, dissipation rate 700 W |
| 3 | cooling unit at front side | Steady state cooling heat flow: 400 W, volume flow of fan: 350 $m^3$/h, ambient temperature: 25 °C, dissipation rate: 700 W |
| 4 | cooling unit at top | Steady state cooling heat flow: 400 W, volume flow of fan: 350 $m^3$/h, ambient temperature: 25 °C, dissipation rate: 700 W |

## 4.1 Arrangement of electronic components

Fig. 4.1 shows exemplary a compact and a rectified arrangement of electrical components in a switch cabinet of fixed size, operated with a fan (operational mode 1, cf. Table 3). The resulting temperature distribution in an intersecting plane of the air volume between the components for compact and rectified arrangement is depicted in Fig. 4.2. The not colored edges in Fig. 4.2 shows the position of frame profiles of the switch cabinet. The temperature of these frame profiles is near the ambient temperature and hence below the lower limit of the temperature legend of Fig. 4.2.

The influence of the compactness of components on the thermal behaviour in a switch cabinet operated with an air/air heat exchanger at the rear side, (operational mode 2, cf. Table 3), is shown in Fig. 4.3.

From Fig. 4.2 and 4.3 it can be recognized that a rectified component arrangement offers the possibility of an improved temperature distribution in the spacing between the electrical components compared with a compact component arrangement. The reason for this is that a narrow neighborhood of components, resulting from a compact component arrangement, constrains the air stream between the components and with that, the removal of locally dissipated heat via enthalpy exchange is affected, too. Moreover, in the case that the components are stressed by a high volumetric dissipation power, whereby high surface temperatures of the components result, distinctive air zones with improper high temperatures may occur.

The reduction of the component compactness is particularly important for operational modes without active air conditioning devices like recirculated-air operations with fans. The use of an air recycling fan makes sense to the destruction of the thermal stratification which occurs during free convection from the bottom to the top of the control cubicle.

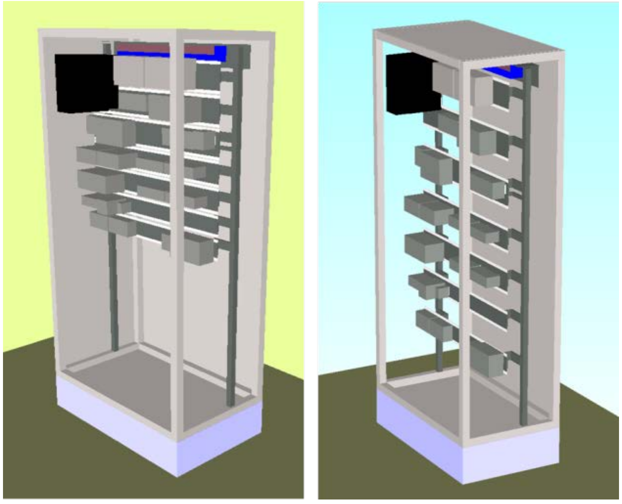

**Fig. 4.1** Compact (left) and rectified (right) arrangement of components.

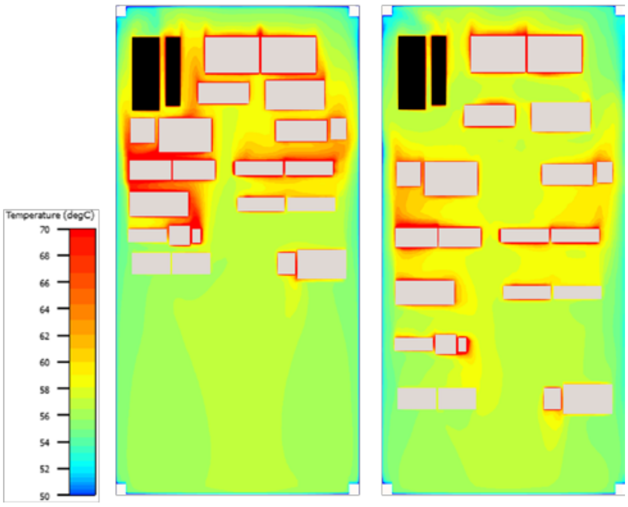


**Fig. 4.2** Temperature distribution between components for compact (left) and rectified arrangement, operating mode 1 (see Table 3).

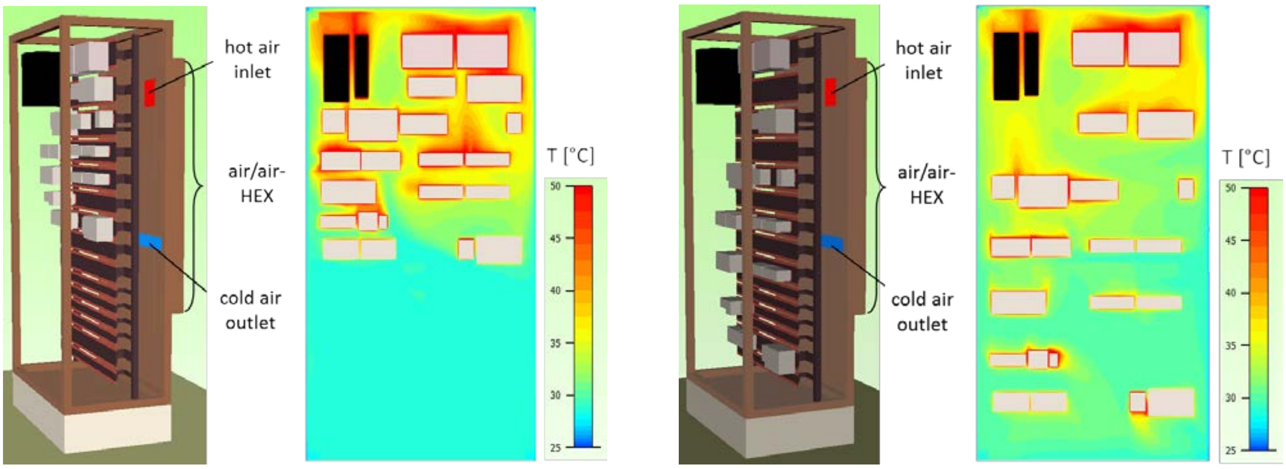


**Fig. 4.3** Influence of compactness on the temperature distribution in a cross section between the electrical components, operational mode 2 (see Table 3).

With the use of active air conditioning devices like cooling units or heat exchangers, a movement of thermally heavily loaded components close to the cold air outlet represents an additional meaningful measure to avoid hotspots and to improve the air conditioning of switch cabinets.

Fig. 4.4 shows exemplary the thermal conditions in a plane between the electrical components for the operation with cooling unit at front side of the switch cabinet (operational mode 3, c.f. Table 3). It becomes obvious that only the switch cabinet area lying between cold air outlet and hot air inlet gets effectively air-conditioned. Electrical components above the hot air inlet are not or only restrictedly circulated with cold air, wherefore the appearance of hotspots is probable in this area of the switch cabinet.

Since the distance between cold air outlet and hot air inlet cannot be changed for a given cooling unit, the component arrangement has to be modified to avoid hotspots. For this purpose components with a great dissipation power are arranged less compact into the proximity of the cold air outlet (c.f. Fig. 4.5 left).

Compared to the initial situation shown in Fig. 4.4, a reduction of the maximum air temperature from 45 °C to 39 °C (c.f. Fig. 4.5 right) results due to these measures. The formation of a hotspot region is avoided.

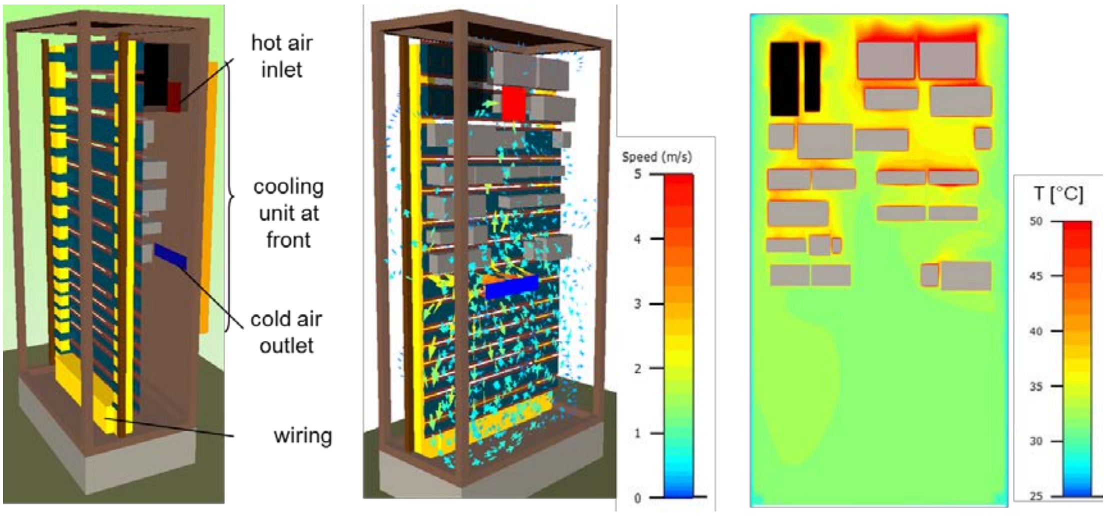


**Fig. 4.4.**: Air conditioning of switch cabinet with cooling unit at front side (operational mode 3, see Table 3), left: set-up, middle: flow field, right: temperature distribution between the components.

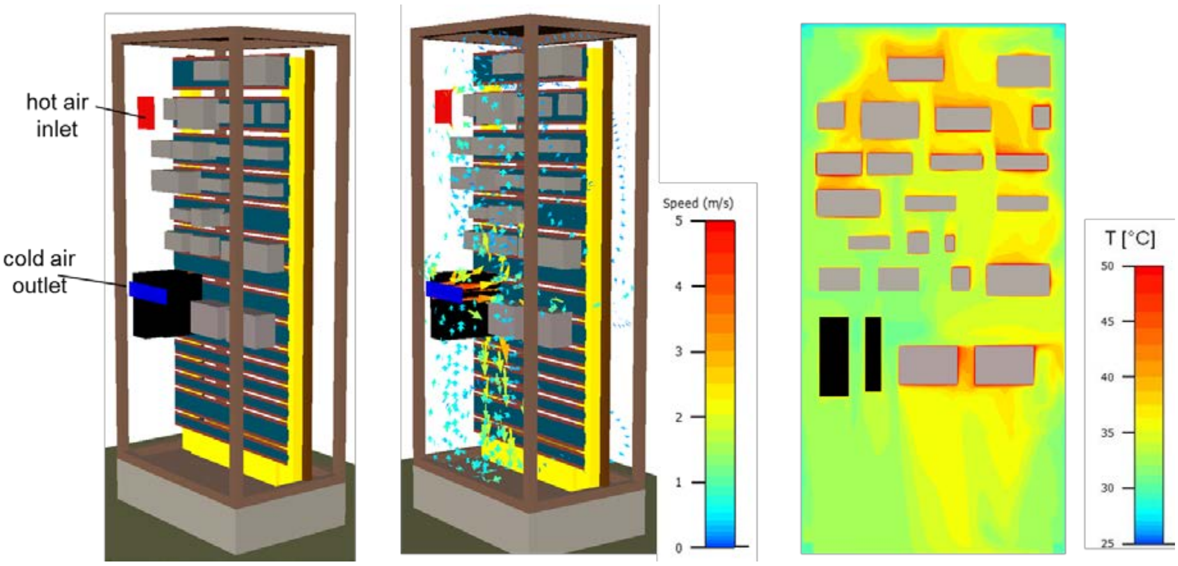


**Fig. 4.5.**: Improved air conditioning of switch cabinet with cooling unit at front side using a changed component arrangement (operational mode 3, see Table 3).

## 4.2 Circulation flow

*4.2.1 Operational mode 2.* Dead zones and cold air bypasses can arise in the switch cabinet at an unfavourable mounting position of an active climate component (heat exchanger, cooling unit). Exemplarily for this state the switch cabinet operation with heat exchanger, mounted behind the LSC wiring system at the rear side (operational mode 2, see Table 3) is shown in Fig. 4.6.

Cold air, normally streaming out to the cold air outlet (see blue cross section in Fig. 4.6) bumps against the back of the assembly webs of the LSC wiring system and splits up into two partial flows. Below the cold air outlet, a recycle flow becomes apparent. Above the cold air outlet, conditioned air is predominantly bypassed to the hot air outlet (red cross section in Fig. 4.6) and, therefore, this part of the cold air flow is ineffective for the air conditioning of the switch cabinet. The cold air, supplied by the heat exchanger, flows predominantly behind the LSC wiring system and not over and between the heat dissipating electrical components. The heat exchanger must get oversized (great U×A, high flow rate) for a sufficient air conditioning of the switch cabinet, so that the static air around the components takes a sufficiently low temperature.

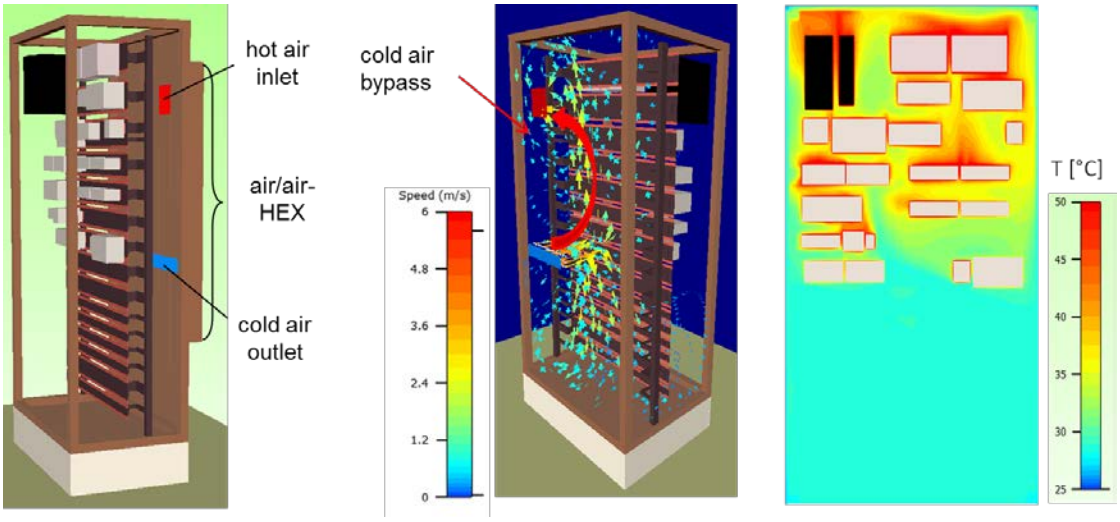


**Fig. 4.6** Set-up (left), flow field (middle) and temperature distribution (right) between electrical components for operational mode 2 (see Table 3) without optimization.

An improvement in the thermal conditions can be induced by producing a circulation flow around the electrical components (c.f. Fig. 4.7). For this purpose, a separating plate may be inserted below the cold air outlet. An assembly web of the LSC wiring system has to be removed and the web gap has to be extended in this region of the LSC framework. Coming from the outlet, the cold air streams forward, is then deflected into the upper zone of the switch cabinet and flows over and around the components. Though, the dissipated power is discharged. The heated air streams to the hot air outlet of the cooling unit at the rear wall.

Using the separating plate, the switch cabinet is subdivided into two zones which are fluidic decoupled. Resting air is below the separating plate and circulating air has to be found above the separating level. Electrical components with no or very low thermal charges can be put in the switch cabinet zone with resting air. Furthermore, the cable supply of the outside can be found in this zone. Components with great dissipation powers have to be put in the upper zone.

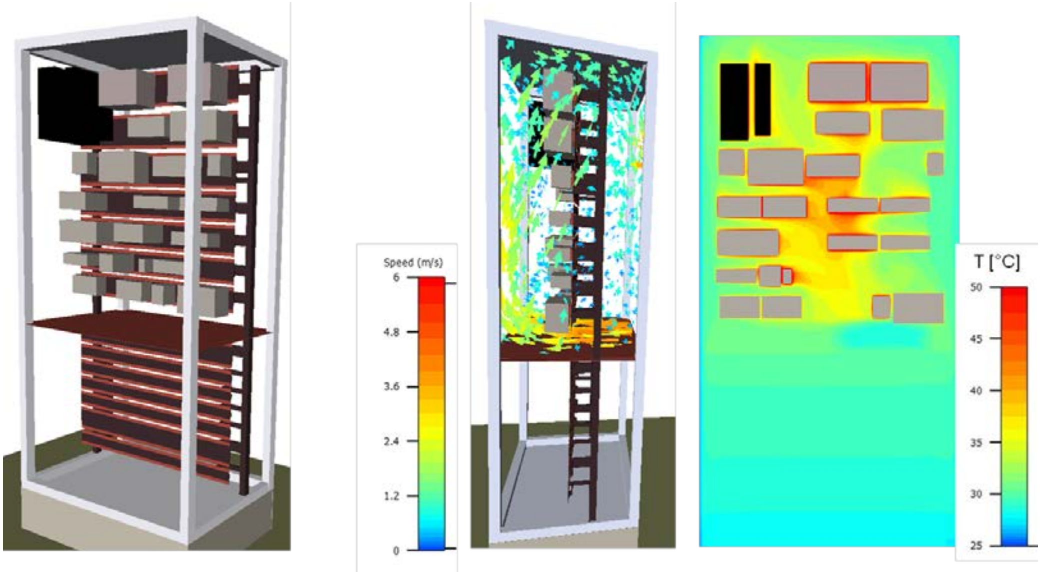


**Fig. 4.7** Set-up (left), flow field (middle) and temperature distribution between electrical components for operational mode 2 (see Table 3) after optimization.

<u>*4.2.2 Operational mode 4.*</u> Cooling units on the roof of the switch cabinet are particularly suitable to produce a circulation flow around the LSC framework. For this, the cold air outlet of the cooling unit can be arranged, for example over the gap between LSC framework and the switch cabinet rear. The hot air inlet has to be placed in front of the LSC framework (see Fig. 4.8). A separation between cold air outflow and hot air suction has to be provided to avoid a flow bypass. This can be achieved by fittings (c.f. Fig. 4.8) or by a great flow velocity (large momentum) at the cold air outlet.

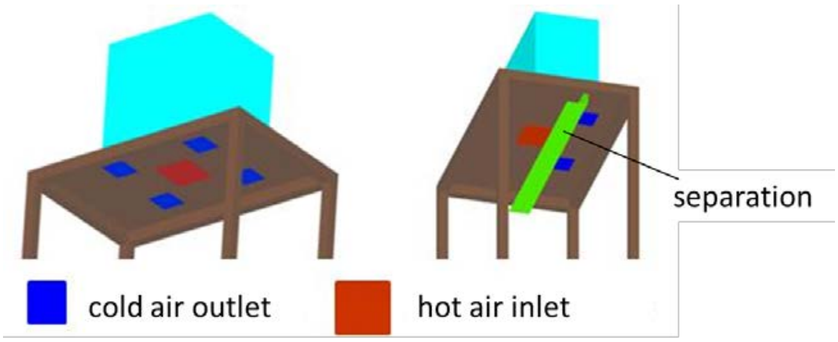


**Fig. 4.8** Setup of cooling units at top with conventional arrangement (left) and optimized arrangement (right) of cold air outlet and hot air inlet.

Compared to a cooling unit at top with conventional arrangement (four cold air outlets placed around one central hot air suction as shown in Fig. 4.8), an improvement of the thermal conditions is recognizable at the operation mode of the cooling unit with circulation flow (two cold air outlets behind the LSC framework, hot air suction in front of the LSC , see Fig. 4.8). These facts are shown in the Fig. 4.9. For the comparison of the cooling units with different arrangements of cold air outlet and hot air inlet, an identical cooling power and the same volumetric flow were assumed for both arrangements.

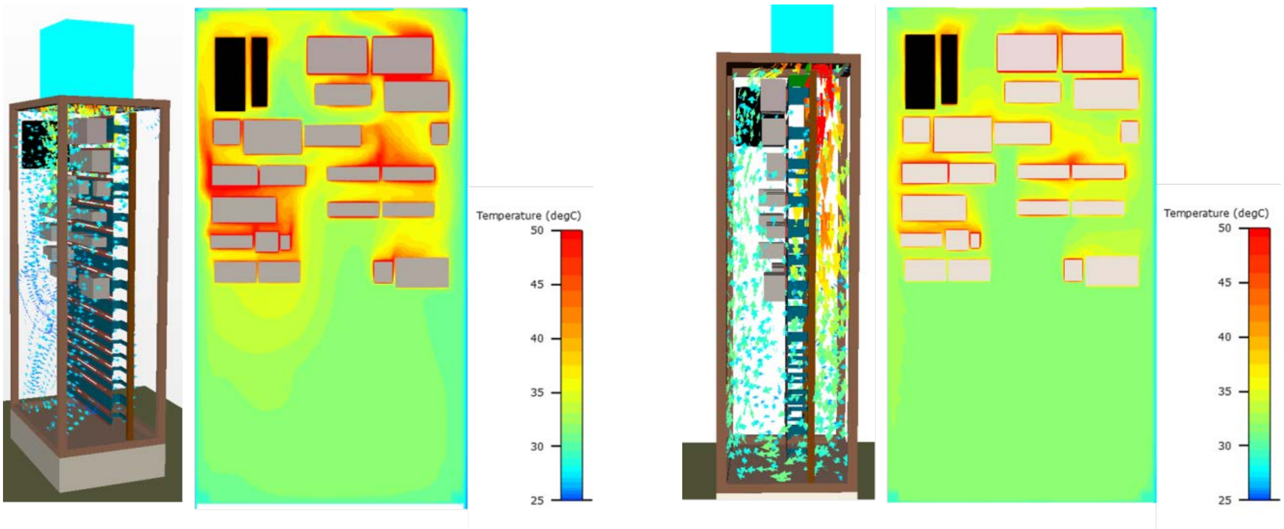


**Fig. 4.9** Temperature distribution between components (grey) at the operation with cooling unit at top, left: not optimized, right: with circulation flow.

## 4.3 Assessment of the potential for energy savings at the cooling of switch cabinets

For the assessment of possible energy savings at the cooling of switch cabinets using optimized internal settings, the flow diagram shown in Fig. 4.10 is suggested. The procedure for the operation with cooling unit is exemplarily shown.

For a not optimized switch cabinet operation with a predefined cooling heat flow $\dot{Q}_{AC}$, an analysis of the thermal situation by creation of the temperature value $T_0$ is carried out. $T_0$ is calculated as the mean value of local temperatures $T(x_i,y_i,z_i)$ at fixed evaluation points i=1, n in a representative cross-section in the air volume between the electrical components . The evaluation points $T(x_i,y_i,z_i)$ are distributed so that, at least, four points occur between every component row at thermally critical and uncritical positions, cf. Fig. 4.10. An optimization of the internal settings of the switch cabinet with regard to flow management, component compactness, component arrangement as well as geometry of the wiring system is then carried out. The thermal situation after the optimization is assessed by means of temperature analysis at the evaluation points and averaging. The average value $T_1$ arises. There is an optimization if $T_1 < T_0$. The cooling heat flow for the optimized switch cabinet is then reduced so that $T_1 = T_0$. The cooling heat flow for this state amounts to $\dot{Q}_{AC,mod}$. The potential for energy savings $\Delta E_{\%}$ can be calculated as

$$\Delta E_{\%} = \frac{\dot{Q}_{AC} - \dot{Q}_{AC,mod}}{\dot{Q}_{AC}} \cdot 100\% \ . \tag{3}$$

$\Delta E_{\%}$ also corresponds to the savings of required power for the cooling unit, if it works with a constant COP (coefficient of performance).

The application of the introduced procedure for the switch cabinet mode with cooling unit at top (operational mode 4, see chapter 4.2.2) yields a theoretical potential for energy savings of 23 % by generation of a circulation flow. For the operation with cooling unit at front side (operational mode 3, see chapter 4.1) no energy savings could be found by the modified component arrangement. Though, the maximum air temperature decreased from 45 °C to 39 °C by the optimization measure.

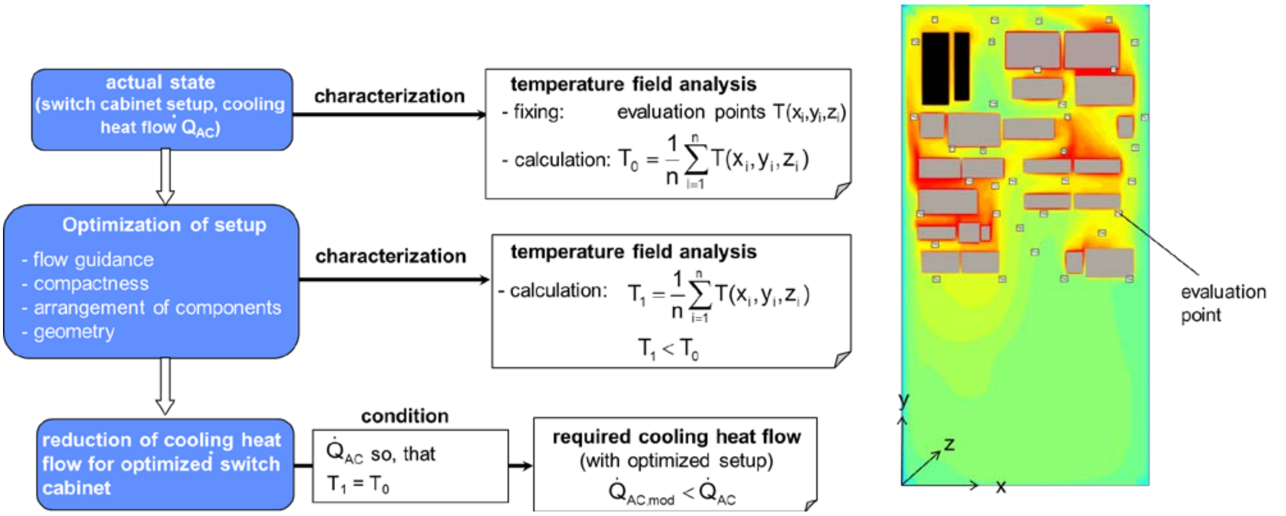


**Fig. 4.10** Determination of energy savings at the cooling of switch cabinets, left: flow diagram, right: example for the fixing of temperature evaluation points.

## 5. CONCLUSIONS

The movement of single components, the reduction of the component compactness and the specific generation of a circulation flow influence the thermal situation of electrical components. These measures have an important impact at the prevention of hot spot areas. Theoretical results for optimized internal settings of switch cabinets show potential for the conservation of cooling energy up to 23% compared to the not optimized initial state.

In order to utilize this potential for energy savings, the future industrial switch cabinet lay-out requires the use of calculation programs for the three dimensional temperature and flow field determination.

## ACKNOWLEDGMENT

The numerical and experimental data base used for this work has been generated in frame of a project of the innovation alliance ‘Green Carbody Technologies‘ (InnoCat 4). The work was supported and financed by Friedrich Lütze GmbH. The authors gratefully acknowledge this support.

## NOMENCLATURE

| | | | | | |
|---|---|---|---|---|---|
| A | surface | ($m^2$) | $\Delta p$ | pressure drop | ($N/m^2$) |
| $d_{hdr}$ | characteristic length | (m) | u | velocity | (m/s) |
| L | length | (m) | $\nu$ | kinematic viscosity | ($m^2/s$) |
| $\dot{Q}$ | heat flow | (W) | $\psi$ | void ratio | (-) |
| Re | Reynolds number | (-) | $\rho$ | density | ($kg/m^3$) |
| T | thermodynamic Temperature | (K) | | | |
| U | overall heat transfer coefficient | ($W/m^2K$) | | | |

## REFERENCES


[1] Styppa, H., *Schaltschrankklimatisierung: Grundlagen, Komponenten, Anwendungen*, Verlag Moderne Industrie, Landsberg/Lech, (1992).

[2] Tierney, J.K., Koczkur, E., Free convection heat transfer from a totally enclosed cabinet containing simulated electronic equipment, *IEEE Transactions on parts, hybrids, and packaging*, Vol. PHP-7, No. 3, (1971).

[3] Du, S.Q., Bilgen, E., Vasseur, P., Mixed convection heat transfer in open ended channels with protruding heaters, *Heat and mass transfer*, Vol. 34, pp. 263-270, Springer-Verlag (1998).

[4] Bessaih, R., Kadja, M., Turbulent natural convection cooling of electronic components mounted on a vertical channel, *Applied Thermal Engineering*,vol. 20, pp. 141-154, Elsevier (2000).

[5] Felczak, M. et al., Optimal placement of electronic devices in forced convective cooling conditions, *Microelectronics Reliability*, Vol. 49, pp. 1537-1545, Elsevier (2009).

[6] Brauer, M., *Grundlagen der Einphasen- und Mehrphasenströmungen*, Sauerländer Verlag, Aarau u. Frankfurt, (1971).

[7] Wirth, K.E., “Pressure Drop in Fixed Beds”, in VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen (GVC), *VDI Heat Atlas*, Second edition, Springer Verlag, pp. 1106-1110, (2010).

[8] Tucker, P.G., CFD applied to electronic systems: A review, *IEEE Transactions on components, packaging,and manufacturing technology* – part A, Vol. 20, No. 4, (1997).

[9] Yang, M.C., 2000, A comparison of using icepack and flotherm in electronic cooling, *Proceedings of 2000 Inter Society Conference on Thermal Phenomena*, pp. 240-246, (2000).