Power over Ethernet Thermal Analysis with an Engineering Mechanics Approach

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Abstract

In recent years, there has been growing interest in utilizing copper Ethernet cables and connections for not only data, but also power for various devices such as VoIP phones, IP cameras, wireless access points, industrial devices, LED lighting systems and remote point of sale kiosks. Being able to combine power (Class 2 low voltage) and control infrastructures into a single jacketed cable offers the potential for faster installations while reducing the materials needed. In this paper, a standard 8P8C RJ-45 Ethernet connector is examined for power applications and found to work for high power Class 2 conditions if the connections remain within specified electrical resistances of the governing standard.

Keywords

RJ-45, Class 2 voltage, PoE, Power over Ethernet, connector, thermal analysis

Nomenclature

Optional listing of terms and units

1. Introduction

The interest in using common data communications hardware for power applications has given rise to various Power over Ethernet (PoE) standards. In 2003, IEEE 802.3af allowed for transmission of up to 15.4W over Ethernet cables mainly to provide power for PoE desktop phones, wireless access points, and certain IP security cameras. In 2009, that limit was increased to 30W with the approval of IEEE 802.3at. This allows for higher power devices, which currently is the industry standard. Cisco Universal Power over Ethernet (UPoE) further increased the maximum to 60W by extrapolating the 30W/2-pairs to use all 4-pairs. Currently, the IEEE is examining the possibility of increasing the limit towards the Class 2 limit of 100W, but IEEE 802.3bt is not expected until 2017 or later.

The rise in power transmission levels and ambient operating temperatures has emphasized the need to accurately model system performance in applications that are not historically IT in nature. Examples include facility infrastructure such as; Heating, Ventilation, and Air Conditioning (HVAC), lighting, security, etc. This topic is particularly interesting since high speed data cables and connections (designed for specific environmentally controlled applications) are now also being used for power transmission in environments that are not as carefully controlled.

In this paper, a standard Ethernet connection system is analyzed where 4 (2-pairs) or 8 pins are used for power. A standard 8P8C connector (sometimes referred to as an RJ45 connector) is analyzed, per IEC 60603-7 [1], where the receptacle is mounted to a printed circuit board (PCB), and the plug connector is attached to a ¼ meter length cable. To simplify the analysis, a single pin/connector model is used with appropriate boundary conditions, and currents up to 0.45A are applied through the connection system. This analysis only examines a system within the normal parameters specified by the IEC; abnormal conditions outside the specification are not included here.

Figure 1 shows a typical jack (receptacle) and plug used in 8P8C systems, along with the mated condition.

Fig 1: 8P8C receptacle (top), plug (middle), and mated assembly (bottom)

2. Problem Set Up - Methodology

The first step is to determine the contact area inside the connector using one of the various methods available. Frequently, a finite element analysis (FEA) is performed to find or simulate the Hertzian contact patch [2-4]. This method works but only provides one contact patch size per analysis. It also assumes one knows the nominal internal geometry dimensions of the connector, which many manufactures will not divulge. Another issue that can hamper the analysis is that the overall governing specification may have tolerance and some significant dimensional changes. This can lead to a number of FEA trials being needed. Using a numerical simulation approach to find and solve the best and worst case conditions is difficult or tedious at best.

Another approach that can help with large variations is to use an engineering mechanics approach to the connector forces. For an 8P8C connector, the applicable standard is IEC 60603-7 and provides the important mating dimensions plus other requirements. For this study, the two key characteristics of connector insertion force and contact resistance (defined in IEC 60603-7) will be focused on. These two allow the problem to be well defined for simulation input values.

With a range of dimensions available for the connectors, another approach to determine the normal contact force (required for the Hertzian contact analysis) is to perform a free body analysis of the connector system. Such a diagram is shown in Fig 2 and is in the same orientation as the mated connector in Fig 1.

Performing an analysis of the free body diagram, Eq 1 is the relationship derived to find the normal contact force.

The friction coefficients ν_contact and ν_plastic are the coefficients for the metallic contact and the internal plastic contact inside the connector. ν_contact is the friction of gold on gold plating in a standard 8P8C connector; this is usually around 0.3 although a range of 0.2 to 0.5 is possible. ν_plastic is the friction from the plug connector to the receptacle connector, and these materials are normally both some form of polycarbonate (PC) plastic. Friction between two PC parts depends upon the load and if any galling of the plastic surfaces occurs. Galling is not an issue in the light normal forces in the connector, and typical friction coefficient ranges from 0.4 to 0.6. In this study, 0.6 was used as value since it conservatively will reduce the contact patch size in the gold plated contacts.

Understanding what effect the above values have on the normal contact force is the key to developing a formula such as this. For example, using a fixed value for the friction coefficients, Fig 3 shows the normal force as calculated from a 20N insertion force.

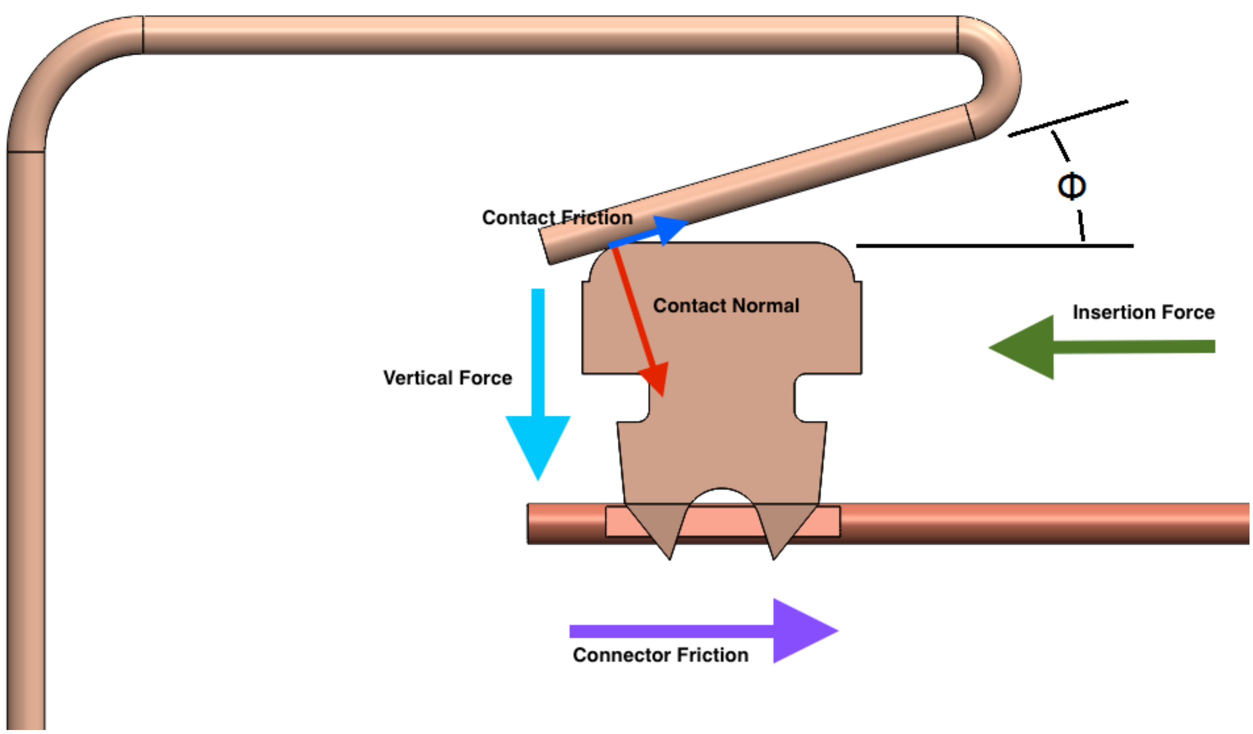

Fig 2: Connector Free Body Diagram

$$F_{normal} = \frac{F_{insert}}{[(\nu_{contact} + \nu_{plastic}) * cos(\Phi) + (1 - \nu_{contact} * \nu_{plastic}) * sin(\Phi)]}$$

Eq 1: Normal Contact Force

Both the plug (a stamped part) and receptacle (normally a bent wire) both have contacts that make an electrical connection as the plug is inserted into the receptacle. Frictional resistance is generated by the contacts and the interaction between the plug and receptacle housing (plastic on plastic) as the plug is forced downward upon insertion.

Another interesting characteristic of this connector system is found when plotting the ratio of the normal force to the insertion force for constant friction values, but over a much wider contact angle range. As shown in Fig 4, it is seen that the normal force has a minimum value in this design.

Another useful plot is to use a fixed angle (16° in this case) with the 20N insertion force and vary the frictional coefficients. A low friction increases the contact force when the insertion force is held constant. In Fig 5, a minimum normal force of 17.1N is generated at friction coefficients of 0.5, while at coefficients of 0 the normal force is 72.6N.

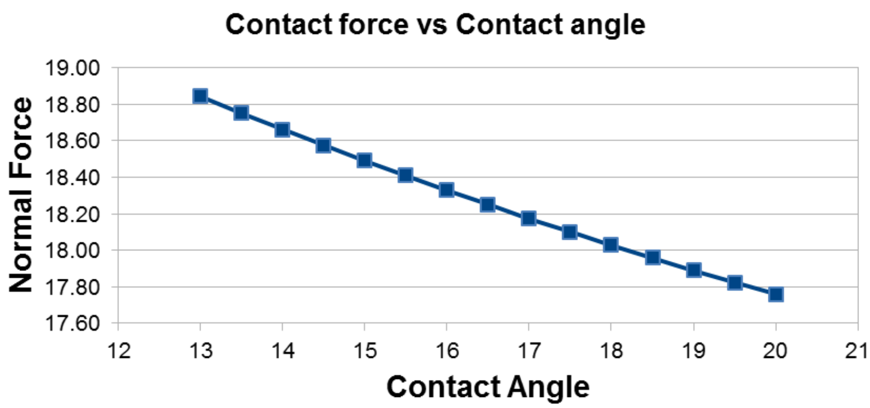

Fig 3: Contact force vs contact angle, contact friction 0.3 and connector friction 0.6

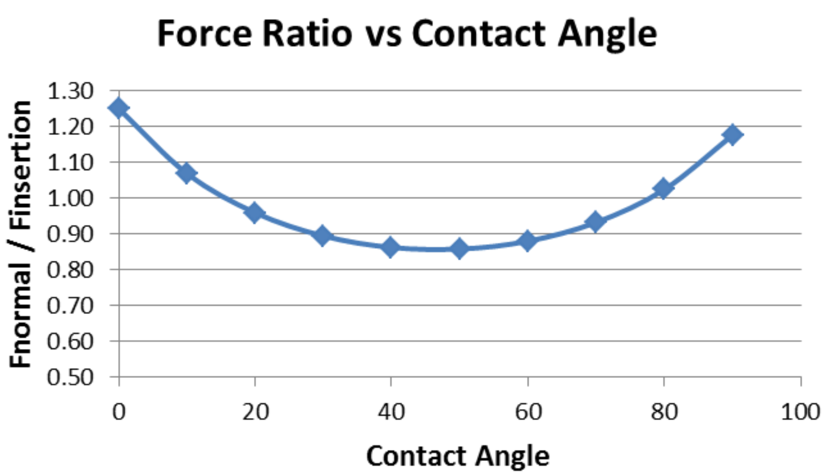

Fig 4: Force ratio vs contact angle, contact friction 0.3 and connector friction 0.5

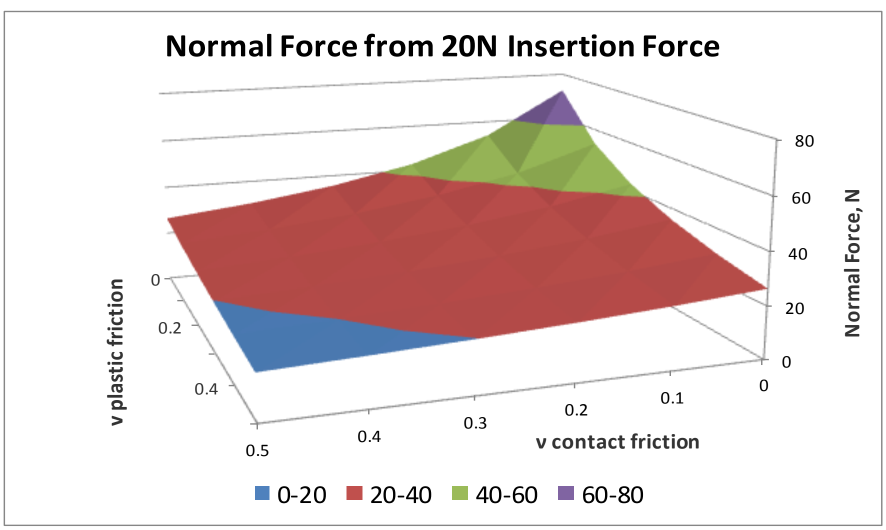

Fig 5: Normal force as varied by frictional forces

With equations such as Eq (1) developed in this approach, several parts of a design can be evaluated quite easily without the need for extensive simulations. This expedites the evaluation of a design and allows for other changes to be considered more quickly. A full numerical simulation can then be done once a final design is selected.

Once the normal force has been determined for a variety of dimensions and materials, the next step is to find the contact patch resulting from this force. The general form of the contact pressure and patch calculations must be used since the two contact surfaces are cylinders at 90° angles to one another. The geometry and material properties are variables that are used in the calculation. These calculations are not discussed here due their complexity and numbers, but this information can be obtained from an external source [5]. For this study, a Mathcad model was created to find the contact patch sizes.

Insertion Force (N)	Contact Force (N), one contact	Contact Patch Size	Contact Pressure, average & peak (MPa)
10	1.06	.21 x .13mm (.0204mm²)	13.1 19.6
20	2.13	.26 x .16mm (.0323mm²)	16.5 24.7

Table 1: Contact Properties

A survey of connector materials used in the metal contacts was also made, and in general the receptacle wire and the male plug parts are made of a phosphor bronze material. No manufacturer who was contacted was willing to state which alloy was used, but the mechanical properties in most connector specifications indicate a C 510 Grade A alloy or similar was used. The electrical conductivities, when specified, were normally higher than C 510; C 510 is 15% IACS but specification sheets showed 25%IACS or higher, so 25%IACS was used in this analysis.

After the contact patch is determined analytically, the two mating parts and their appropriate indentations are created using solid modeling computer aided design (CAD) software. Surface to surface contact is enforced in the model at the patch surfaces. This is the most complicated step in this approach and certain CAD operations must be performed to obtain the correct geometry.

A typical contact patch for the connector is shown in Fig 6.

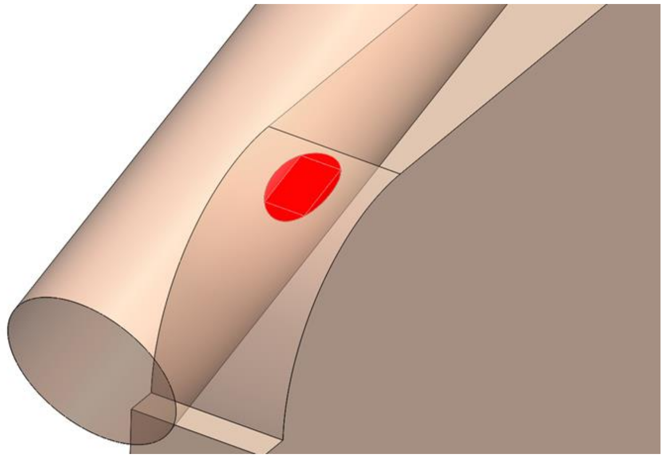

Fig 6: Typical contact patch area

The last key unknown in the thermal model is the thermal resistance at this contact patch area. There are several methods using surface and macro-roughness calculations (for example, see [6]), but again there is a general method which uses the electrical resistance of a connection. That formula is:

$$R_{th} = \frac{R_c}{K * \rho} \qquad [2]$$

Where Rth is the thermal resistance of the contact patch, Rc is the electrical contact resistance, K is the thermal conductivity of the interface material and ρ is the electrical resistivity [3]. This model is useful since the contact patches are very small and the heat flow is contained through a very small area (essentially 1D). Once again, using the specification for the connector's maximum electrical resistance (20 mΩ), the thermal resistance can then be calculated. This method gives values of Rth bounded by typical values of similar contact resistances found in literature and data handbooks [7-8]. For this analysis, the values of Rth used from equation (2) are shown in Table 2.

R_c (mΩ)	R_{th} (K/W)
10	1741
20	3481

Table 2: Connector Thermal Resistances

3. Thermal Model

Thus, using the specifications of the 8P8C connector from IEC 60603-7, along with a free body diagram analysis, a full thermal model can be created. As mentioned earlier, only one of the eight pins in the system was modeled, along with the heat dissipation path from the PCB to the cable insulation. This is shown in Fig 7.

4.

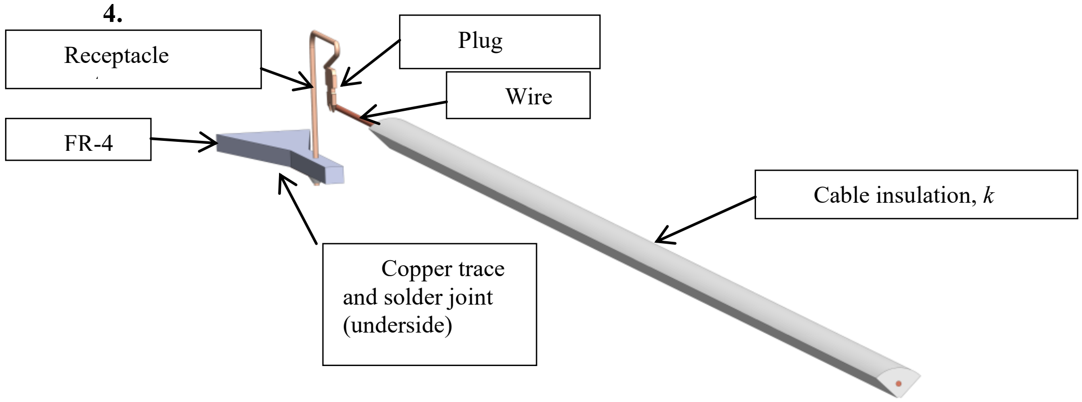

Fig 7: 3D Model of one pin system

To solve this problem, a commercial computational fluid dynamics (CFD) program was used (SolidWorks Flow Simulation) but only in a conduction mode. An electrical current is specified for the entire path (this supplies the joule heating in the solid electrically conducting parts) and appropriate contact resistances, both electrical and thermal, are specified at mating surfaces. The environmental boundary conditions were chosen as fixed heat transfer coefficients to simulate somewhat open conditions (5 W/m^2-K) or very tightly packaged situations (1 W/m^2-K). The heat generated in the receptacle primarily flowed into a copper pad via a modeled solder joint and into an FR-4 PCB, which then dissipated heat via the environmental boundary condition. The outer surface of the 8-conductor cable provided the heat transfer to the cable's environment, and removed heat from the plug contact and wire. In certain cases where the two boundary condition temperatures were far apart, some heat would flow through the actual connector contact toward the cooler side.

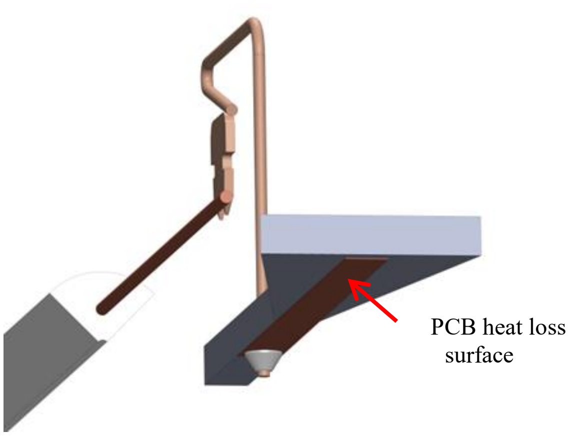

Fig 8: PCB Heat loss surface

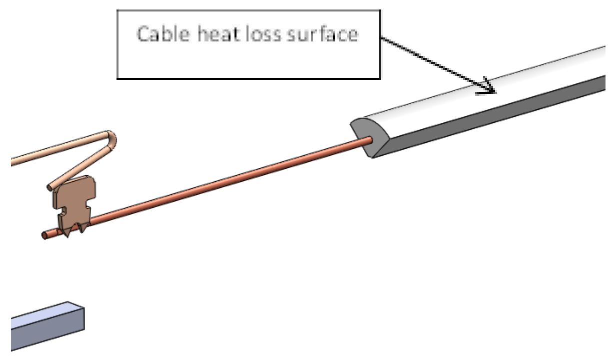

Fig 9: Cable heat loss surface

5. Thermal Analysis Results

Sample results along with a table of various cases solved are shown in Table 3 and Figure 10.

From the results in Table 3 it is apparent that the ambient environmental boundary temperatures have the greatest effect on key temperatures of the connector contact, the PCB average temperature, and the external cable temperature. The length of the external cable involved in dissipating heat was also influenced by these environmental temperatures. The other factor affecting final temperatures is the heat transfer coefficients used. As expected, a tightly packaged cable bundle or power supply enclosure with little air flow will cause significant temperature increases.

Interestingly, the amount of temperature change caused by a 20 or 10N contact force is not much, around 0.2°C or less in the cases evaluated. The contact area with a 20N insertion force and friction coefficients of .4 and .6 for $v_{contact}$ and $v_{plastic}$ respectively is around 0.03232 mm^2, while a 10N insertion force has an area that is 37% less at 0.02036 mm^2. It is likely any surface corrosion or change in the contact surface producing high resistances would change this. Regardless, any change in the condition would no longer be a connector system within the IEC 60603-7 specification.

Table 3: Simulation cases and results

RJ45 Connector Test Matrix	Ambient Temp, Cable	Ambient Temp, PCB	Insertion Force, N	Heat Transfer Coeff from PCB	Heat Transfer Coeff from Cable	Input current, A	Electrical contact R, receptacle to plug	Electrical contact R, plug to wire	Results			
			20N max	5 W/m^2-K max	5 W/m^2-K max		20 mΩ max	40 mΩ max	Plug to receptacle contact temp, max	PCB average temperature	External cable temperature, max	Cable temperature gradient length, mm
Case												
Best Case	40	40	20	5	5	0.45	10	20	48.8	43.9	45.4	100
Worst Case	60	60	10	1	1		20	40				
1	30	60	10	5	5	0.3	20	40	57.7	60.0	36.0	100
2	50	80	10	5	5	0.3	20	40	78.1	80.1	56.1	100
3	30	60	20	5	5	0.3	20	40	57.6	59.9	36.0	100
4	50	80	20	5	5	0.3	20	40	78.0	80.1	56.1	100
5	30	60	10	5	5	0.45	20	40	67.0	63.6	40.3	150
6	50	80	10	5	5	0.45	20	40	87.7	84.0	60.5	150
7	30	60	20	5	5	0.45	20	40	66.9	63.5	40.3	150
8	50	80	20	5	5	0.45	20	40	87.6	85.3	60.5	150
9	30	60	10	1	1	0.3	20	40	61.9	62.7	44.1	>250
10	50	80	10	1	1	0.3	20	40	82.7	83.4	64.4	>250
11	30	60	20	1	1	0.3	20	40	61.8	62.6	44.1	>250
12	50	80	20	1	1	0.3	20	40	82.6	83.3	64.4	>250
13	30	60	10	1	1	0.45	20	40	83.4	79.5	57.0	>250
14	50	80	10	1	1	0.45	20	40	105.1	101.2	77.8	>250
15	30	60	20	1	1	0.45	20	40	83.2	79.3	57.0	>250
16	50	80	20	1	1	0.45	20	40	105.0	101.0	77.8	>250

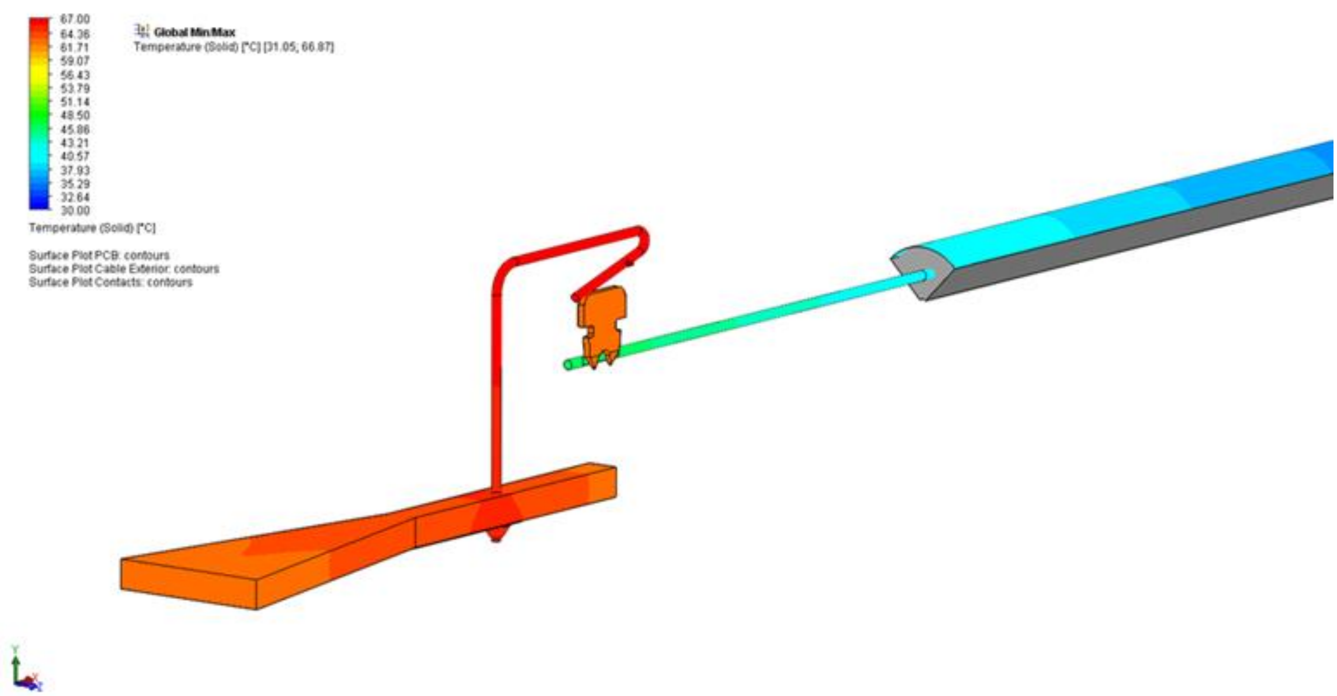

Figure 10: Case 7 temperature results

6. Conclusions

Using an engineering mechanics approach allows for the understanding of various possible connector conditions and evaluates them without resorting to direct FEA analysis of the contact region. This mapping of connector variables enables a broader understanding of the key variations in a design in quicker fashion.

In this particular example, an 8P8C (RJ-45) connector is shown to have adequate cooling for Class 2 power loads when standard Joule heating of parts and electrical contact resistance heating is within the connector specifications.

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