

# Thermal cut-off response modelling of universal motors

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**Abstract.** This paper presents a model to predict the thermal cut-off (TCO) response behaviour in universal motors. The mathematical model includes the calculations of heat loss in the universal motor and the flow characteristics around the TCO component which together are the main parameters for TCO response prediction. In order to accurately predict the TCO component temperature, factors like the TCO component resistance, the effect of ambient, and the flow conditions through the motor are taken into account to improve the prediction accuracy of the model.

**Keywords:** Thermal model, Universal motors, Thermal cut-off, Heat and mass transfer.

## 1. Introduction

Thermal cut-off unit, or more commonly known as TCO, is a mechanical device that functions through an increase in resistance when there is rise in temperature [1]. When the temperature reaches a designated calibration temperature, the bimetallic strip snaps open and breaks the circuit [2]. The bimetallic strip will return to its original position after it is allowed to be cooled down, as shown in figure 1.

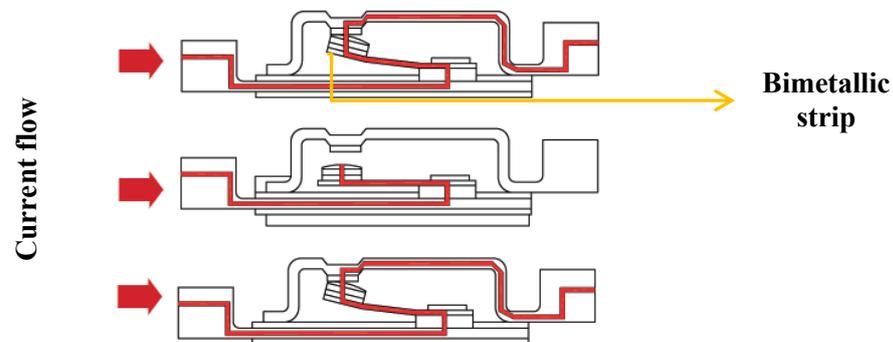
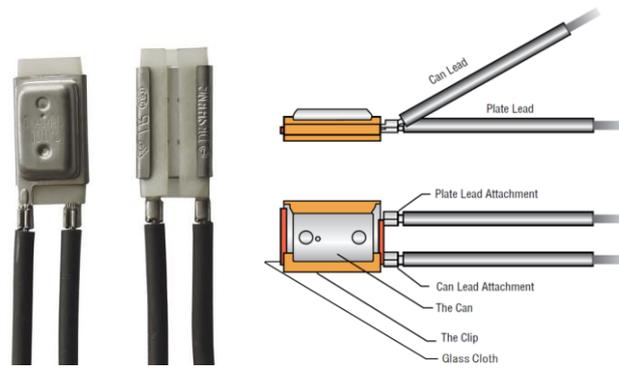


Figure 1. TCO bimetallic strip operation. [3]

A typical TCO usually consists of a bimetallic strip, a metal casing, and a protective glass cloth as shown in figure 2.



**Figure 2.** Typical TCO and its schematic. [3]

TCO's are used widely in many small motors that are present in electrical appliances. In the case of universal motors, the waste heat generated by windings and bearings is an example of unwanted heat. The TCO acts as a protection for the motor when the motor overheats/current overloads during abnormal operation. A motor will overheat when it is overloaded for either an extended period of time or on a frequency basis [4]. Placement of the TCO on the motor is important since the accuracy of the TCO can be affected significantly by load variations and flow characteristics within the motor [5]. With this in mind, the TCO is usually placed at the hottest practical location inside the motor. For example, a TCO is placed at near electric motor's winding so that TCO can activate in time if the motor winding overheats, as shown in figure 3.



**Figure 3.** TCO inside a universal motor.

Choosing a correct bimetal type for a particular application is crucial to ensure the TCO functions as required. According to Kanthal [6], the factors affecting bimetal operation are operational temperature and deflection, mechanical stress, electrical resistivity, thermal conductivity, corrosion resistance, and machinability. The operating condition of a motor is crucial when selecting a proper TCO to be used inside a motor. For a universal motor, amongst the main parameters that affect TCO selection are the electrical current, the motor winding insulation class, and the motor minimum flow rate. Apart from these parameters, the overall construction of motor, position of TCO and its internal resistance will also affect the working characteristic of a TCO. The TCO used in a motor has to achieve a balance between protecting the motor from overheated condition and avoiding nuisance tripping (early cut-off).

In order to avoid undesirable TCO cut-offs, it is crucial to understand the TCO response behaviour and the operational window in any electrical appliance that uses universal motor. This operational window is the margin between which the TCO activates before motor failure and nuisance tripping. In this study, the TCO response model is being developed to help understand TCO's response towards ambient temperature, operating flow rate, electrical current, and TCO resistance. By doing this, the thermal risks of any TCO dependent appliance can then be evaluated to provide sufficient margin

between the TCO tripping at motor overheat condition/current overload and nuisance tripping at normal use.

The studies [5] [9] done by other researchers so far are focused on the motor thermal protection model mainly through the use of resistance temperature detectors (RTD) or positive temperature coefficient (PTC) thermistors. TCO's that are widely used in many small universal motors for its inexpensive design has not been studied much in detail. The present paper aims to make a motor thermal protection model which is based on TCO wherein it will also quantify its variations from various factors.

## 2. Mathematical Model

The mathematical model for TCO response prediction includes formulating a thermal model based on heat transfer from motor windings to the TCO unit. This model can be divided into two: first by modelling heat transfer from windings to the exhaust air and secondly the heat transfer from the exhaust air to the TCO component.

The thermal model for the heat transfer between the windings and the exhaust air is made by comparing the resistive heating of motor windings, thermal resistance of the system and thereby calculating the temperature rise of the exhaust air based on its thermal capacity, as shown in equation (1).

$$I^2(R_f+R_a) - \frac{\Delta T}{R} = \dot{m}C_p\Delta T \quad (1)$$

In equation (1),  $I$  is the current passing through the motor circuit,  $R_a$  is the armature coil resistance,  $R_f$  is the field coil resistance,  $R$  is the thermal resistance,  $\dot{m}$  is the mass flow rate,  $\Delta T$  is the temperature difference between the exhaust and TCO surface and  $C_p$  is the specific heat capacity of air.

Based on equation (1), the thermal model terms are rearranged into an iterative transient model [7] as shown in equation (2).

$$T_n = \left[ \frac{I^2}{\tau} dt + T_{n-1} \left( 1 - \frac{dt}{\tau} \right) \right] \quad (2)$$

where  $\tau$  is the time constant,

$T_n$  is the exhaust air temperature at time  $n$  (expressed in units of  $I^2$ )

$T_{n-1}$  is the exhaust air temperature at time  $n-1$  (expressed in units of  $I^2$ )

The final exhaust temperature is multiplied by  $(R_f + R_a)R$  to get the temperature in unit of degree Celsius.

The incremental form of equation (2) is ideal in calculating the real time temperature response. The transient nature of this model would also make it easier to calculate the winding resistance when it changes as a function of temperature.

The thermal model for the heat transfer between the exhaust air and the TCO surface is a steady state temperature calculation compared to equation (2) which is time dependent. The steady state model is made with the assumption that the convective heat transfer is the major contribution to the temperature rise compared to the other heat transfer modes. This is a reasonable assumption to make since radiation is not going to be significant at such low temperature range of 20°C to 150°C as compared to forced convection. As for conduction, most motor designs have TCO units primarily held in the direction of airflow by negligible contact to solid parts. Even in cases where they are primarily attached to solid parts, the part they are attached to is a plastic surface which has poor thermal conductivity. These assumptions help to reduce the complexity of the model.

The steady state model can be derived for a thermal condition where the TCO surface and the motor exhaust air have achieved thermal equilibrium. At this state, the heat produced by the TCO is equal to the heat dissipated through the motor exhaust air. This is shown in equation (3).

$$I^2R_{TCO} = hA(T_{TCO} - T_{exhaust}) \quad (3)$$

In equation (1),  $R_{TCO}$  is the TCO component resistance,  $A$  is the flow facing surface area of TCO,  $T_{TCO}$  is the temperature of the TCO component and  $T_{exhaust}$  is the temperature of the motor exhaust air.

By rearranging the terms, we would arrive at equation (4) which can be used to calculate the steady state TCO surface temperature.

$$T_{TCO} = \frac{I^2 R_{TCO}}{hA} + T_{exhaust} \quad (4)$$

The heat transfer coefficient  $h$  value in equation (4) is derived from equation (5).

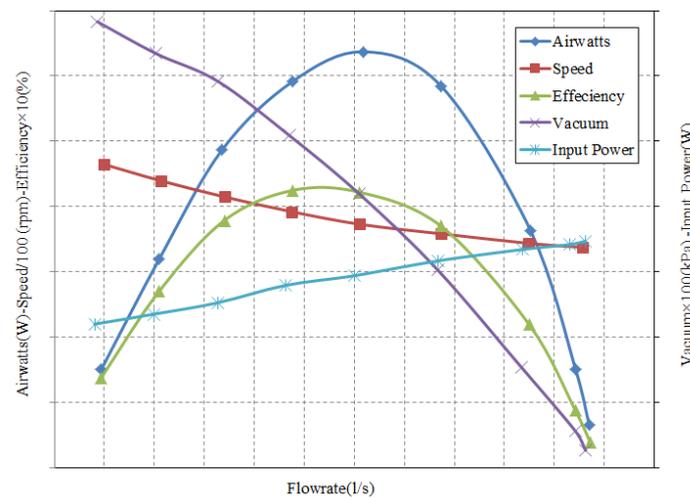
$$h = \frac{Nu k}{l} \quad (5)$$

where  $Nu$  is the Nusselt number that is calculated using  $Re_D$  and  $Pr$  which are the respective Reynolds and Prandtl number. The below equation is derived based on the condition of flow around rectangular solids [8].

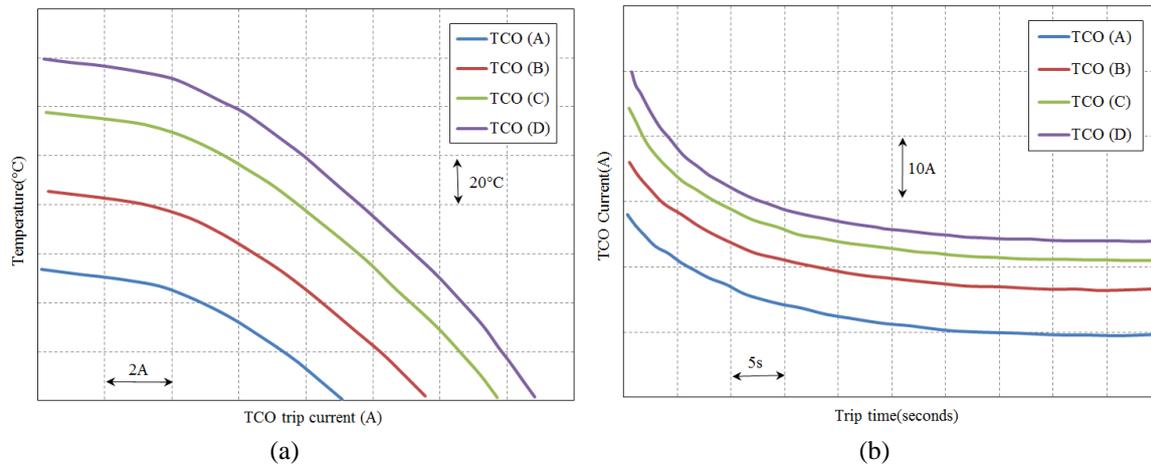
$$Nu = 0.158 Re_D^{0.638} Pr^{1/3} \quad (6)$$

The flow characteristics around the TCO would be different for different TCO design configurations. Based on the relative location of TCO in the motor, certain parameters like the velocity of air over TCO, the characteristic length for Reynolds number, and the heat transfer coefficient around TCO would be changed in the model.

To make this predictive model without the need of additional testing, the input data for the proposed thermal model is taken from the supplier datasheets of universal motor and TCO component. Sample data are shown in figure 4 and figure 5.



**Figure 4.** Universal motor supplier datasheet displaying motor performance data.



**Figure 5.** TCO unit supplier datasheet displaying (a) Trip current vs. TCO temperature and (b) Current vs. Trip time.

Based on figure 5 (which contains data taken from a standalone TCO unit), it can be inferred that the TCO unit trips to protect the motor at lower temperature for higher current. This is due to the fact that the TCO unit is using a bimetallic strip circuit breaker that trips when the strip reaches a particular temperature at a certain current. When higher current travels through the strip, the resistive heating due to the current would make the TCO unit to trip at lower operating temperature. Using this knowledge, it is possible to estimate the resistance and temperature coefficient of the TCO component, as shown in equation (7).

$$R_{TCO} = \frac{hA\Delta T}{I_{trip\ current}^2} \quad (7)$$

where  $I_{trip\ current}^2$  is the current at which the bimetallic strip snaps and breaks the electric circuit. Using equation (7), the resistance of TCO can be estimated at all TCO trip temperatures range provided in the supplier datasheet. The temperature coefficient of resistance  $\alpha$  is estimated by selecting the highest resistance,  $R_{high}$  and lowest resistance,  $R_{low}$  values from all the resistance values calculated from equation (7) and using it in equation (8).

$$\alpha = \frac{R_{high} - R_{low}}{R_{high}(T_{high} - T_{low})} \quad (8)$$

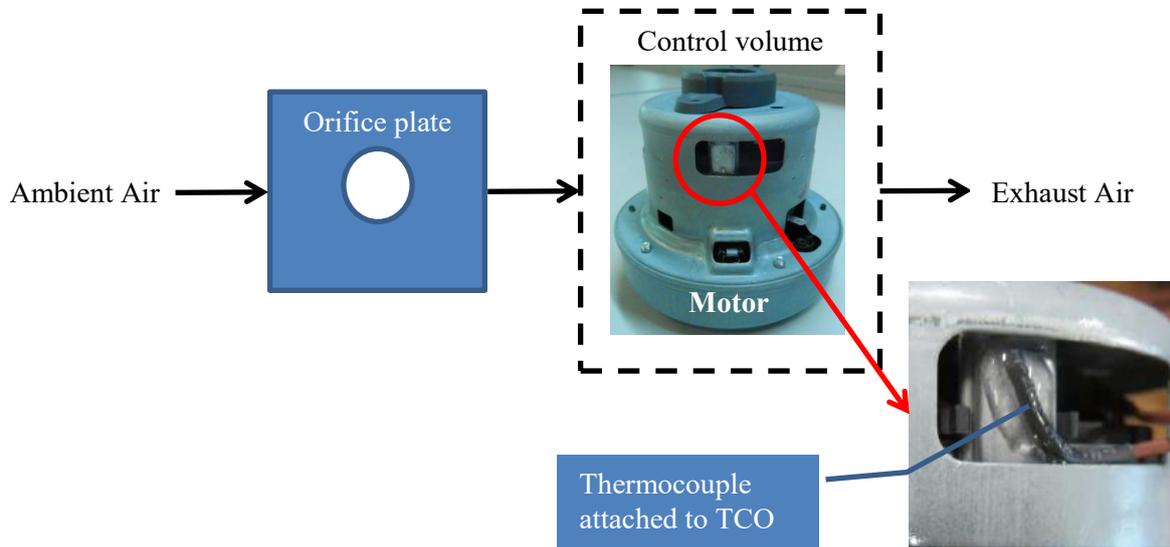
The above two information would be stored as reference for each category of TCO variants such that the thermal model would refer the resistance and the temperature coefficient of resistance to estimate the resistance of the corresponding TCO in the available TCO temperature range. Equation (9) will be used to calculate this when the TCO temperature increases from  $T_1$  to  $T_2$ .

$$R_2 = R_1[1 + \alpha(T_2 - T_1)] \quad (9)$$

### 3. Experimental Methodology

The experimental setup for measuring the TCO surface temperature is done based on the schematic shown in figure 6. The TCO connected to the universal motor is placed inside a control volume/appliance. The current passing through the motor is measured using a Yokogawa digital power meter WT210. The resistance of the TCO is checked using a Fluke 8845A 6-1/2 digit precision multimeter before the test starts. One T-type thermocouple is attached to the TCO surface to measure

the temperature, which is continuously logged by a Pico Technology USB TC-08 data logger. The flow rate passing through the motor is measured by an orifice plate at the motor upstream. The flow rate is varied by changing the orifice plate diameter.



**Figure 6.** Schematic diagram of experimental test.

An uncertainty budget is made for each of the parameters measured and controlled during the test (as show in table 1). The terms I, R-TCO, Q, and T-Amb are the current passing through the motor, TCO resistance, flow rate and ambient temperature measured during the test.

Based on the uncertainty budget calculated in table 1, the expanded uncertainty of the TCO surface temperature value is  $\pm 4.79^\circ\text{C}$  at 95% confidence level. The expanded uncertainty  $U_{exp}$  is as expressed in equation (10).

$$U_{exp} = k_c \times U_{comb} \quad (10)$$

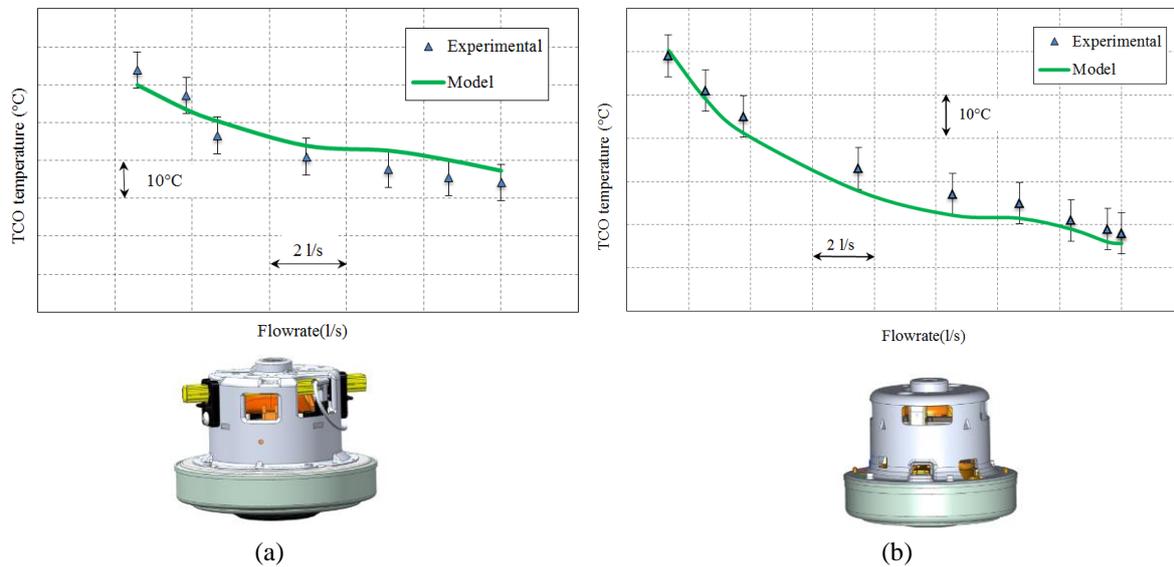
where  $k_c$  is the coverage factor and  $U_{comb}$  is the combined standard uncertainty.

**Table 1.** Uncertainty budget for the TCO surface temperature measured during the test

Symbol	Source of Uncertainty	Value	$\pm$	Probability distribution	Standard Uncertainty
Random	Repeatability		0.2593	Normal	0.26
I	Power meter accuracy	10	0.0100	Rectangular	0.46
I	Resolution error	10	0.0010	Rectangular	0.05
R-TCO	Multimeter accuracy	0.01	0.0002	Rectangular	0.18
R-TCO	Resolution error	0.01	0.0001	Rectangular	0.09
Q	Flow rate Accuracy	10	0.1256	Rectangular	2.82
T-Amb	Calibration uncertainty	40	0.6050	Rectangular	0.35
		Norm/Rect	0.09	Combined Std Uncertainty ( $\pm$ )	2.90
		Coverage factor	1.65	Expanded Uncertainty ( $\pm$ )	4.79

#### 4. Results and Discussions

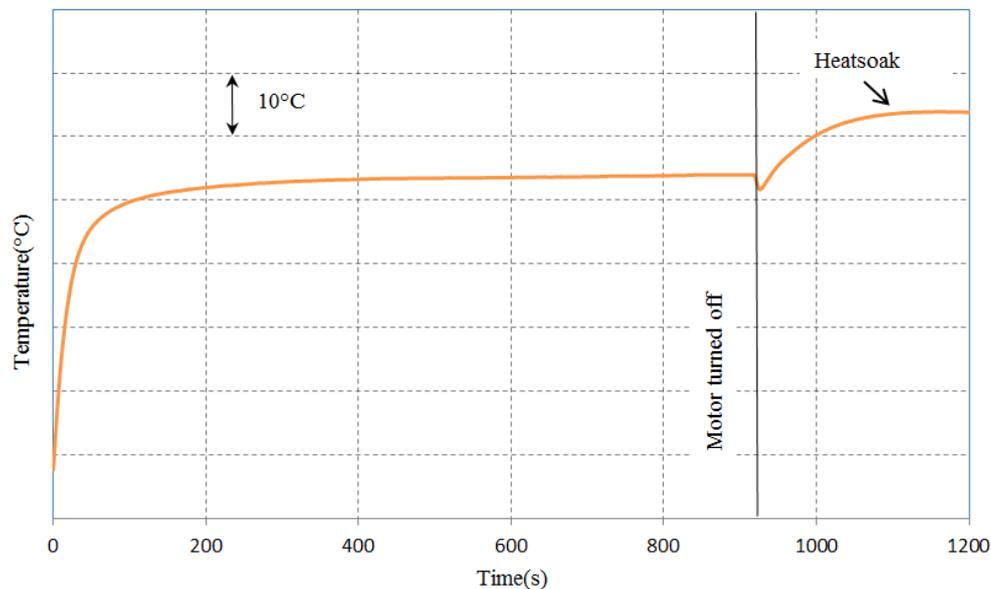
The proposed thermal model is validated by comparing its prediction with the experimental data. The model is compared with the TCO surface temperature test data from two of the most widely used commercial universal motors.



**Figure 7.** Comparison of model and actual test data for (a) High power range universal motor (b) Low power range universal motor.

Based on figure 7, we can observe that the model is satisfactorily following the trend of the actual TCO surface temperature. The maximum difference between the test data and model data is 6.4% for the high power range vacuum motors while for the low power range, maximum difference of 7.3% can be observed. The difference in results can be partly explained by the limitations of the model where the prediction is based on a single time constant. In reality, the system would compose of many components, where each component has different thermal time constants and thus achieving different steady state temperature results. This can also be realized from the fact that at short time intervals, the thermal response is dominated by the heat transfer from the stator and rotor conductors to the iron while for longer time intervals, the thermal response is dominated by the heat transfer from the iron to cooling air [9]. Another reason for the discrepancy between the actual test data and the model data can be due to the varying efficiency between different vacuum motor samples.

While checking the logged surface temperature of the TCO component, it was observed that the TCO surface did not immediately cool down after the motor was switched off. In fact it had been heating up due to the phenomenon called thermal or heat soak [10] (as shown in figure 8). In universal motors, heat soak can be theorized to happen due to two reasons. Firstly, it is due to the thermal lag between the heat generating TCO and the cooling flow on the TCO surface. Secondly, it could be due to the relative position of the TCO unit that makes it susceptible to be on the receiving end of the heat dissipated by natural convection from the windings. Both these reasons will lead to an increase in TCO temperature after the motor stops running.

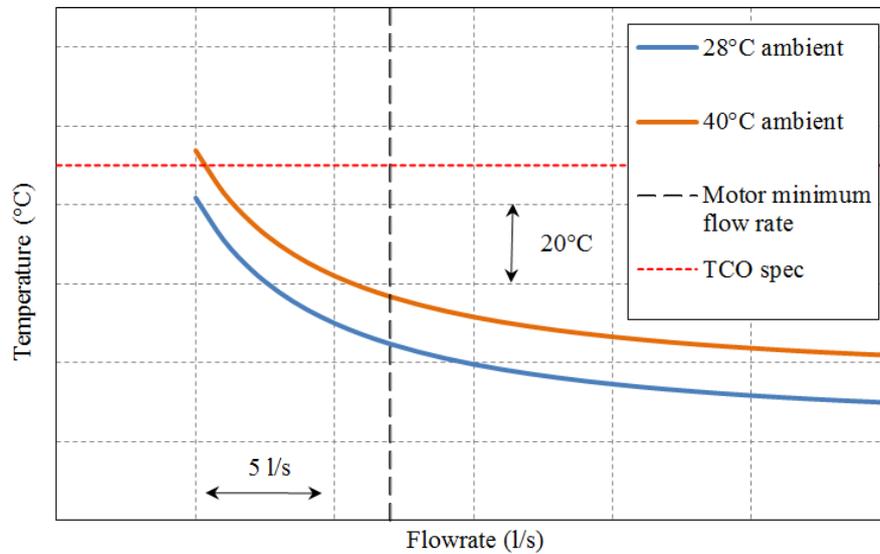


**Figure 8.** Temperature profile data of TCO surface temperature.

Also, it is observed that the very high inrush current going to the TCO during start can cause the bimetallic strip to reach the trip temperature at a short moment thereby making steady state comparisons of the model invalid for those scenarios.

The inrush current coupled with heat soak can prove to be a risky combination wherein the TCO unit might trip soon after the motor has reached the heat soak peak during switch off and immediately switched on. This type of scenario can actually cause pre-mature tripping. Thus the model has some real world limitations, which was not addressed in this model. For effective modelling of the TCO response, the response modelling should include the effects of the heat soak and inrush current to provide a better design guideline for using the TCO component in universal motors.

The final result of the model is used to predict the surface temperature of the TCO as shown in figure 9. Figure 9 indicates the temperature profile of TCO surface temperature at 28°C and 40°C environment which are the boundaries for TCO specification validation. Based on this graph, inferences can be made whether TCO surface temperature meets the TCO design criteria. The criteria are based on whether the predicted TCO trip temperature is within the design margin. If the predicted TCO surface temperature is not within the design margin, i.e. the TCO surface temperature is less than the TCO trip specification at the minimum flow rate (defined by the motor supplier as the temperature of the TCO should have reached when the motor is running at minimum flow rate) or the TCO surface temperature is very close to the TCO trip specification at normal flow rate conditions, changes in TCO design criteria has to be made. Changes can be done by lowering the TCO resistance, or by using a TCO with higher trip temperature rating and in some cases both.



**Figure 9.** Graphical results of the TCO surface temperature prediction model.

## 5. Conclusions

This paper presented a mathematical model for predicting the TCO response characteristics for universal motors using a combination of transient and steady state heat transfer model. The thermal interactions within the universal motors which influence the TCO surface temperature is taken into account using a mathematical model that is based on inputs from various universal motors and TCO component supplier datasheets. The model can help to estimate the TCO operating temperature under various conditions, and prescribing a suitable TCO to be used in the motor.

In order to perform a more comprehensive study on the TCO response with the effects of heat soak and inrush current, the entire model needs to be modified to a time dependent one. The more comprehensive model with heat soak and inrush current will be most valuable to accurately predict the working window for TCO at different operating constraints.

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