

# THERMAL HUMAN MODELING : DESCRIPTION AND APPLICATIONS

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## ABSTRACT

*This paper focuses on the description of a computer model named ATHOM which concerns the thermal behaviour of the human body and its exchanges with the environment through clothing. Dassault Aviation developed this tool so as to address issues relevant to thermal stress. This gives potential to improve pilots performance and comfort through clothing and Environmental Control System. From the input data of mission, environmental, clothing and subject parameters, the models computes variables which can be related to evaluation criteria (core temperatures, skin temperatures, heat storages...). The application to pilots cases shows the criticality of the pre-flight phases. The quantification of these phases allows to compare and specify solutions for improvements.*

## INTRODUCTION

Thermal stress is an important point of concern for military aircrafts. This field of study is related to a lot of parameters, external and internal to the aircraft structure (outside climate, Environmental Control System, clothing, mission...). Its importance stands mainly in a significant impact on pilot's performance and safety, especially in hot climates which is commonly considered as the most critical case of the problem. Dassault Aviation is committed to thermal comfort and in order to improve pilots performance and comfort, Dassault Aviation developed and uses a computer model which is described hereunder.

Available data or specification related to thermal stress is usually applicable only to very specific thermal environments, types of clothing, limited range of metabolic rates and kind of Environmental Control System. Consequently, it is difficult to pick up adequate data corresponding to a particular global thermal system to be studied. Hence, there is a need to model the situations to be analysed so as to evaluate the case under study, with the man in the loop.

Thermal modeling of the human body is a difficult field of study. On a complexity scale, it can be located somehow between anthropometrical /biomechanical modeling and cognitive modeling, while being related to these two domains. Among other factors, thermal behavior of the human body depends on the characteristics of the subject and it also involves cognitive and subjective parameters.

This paper will go through:

1. An overview of theoretical features in a first step.
2. A presentation of the computer model in a second step .
3. A discussion about evaluation criteria.
4. A description of applications.

## THERMAL MODELING

Thermal modeling is commonly based on a thermal balance analysis involving internal heat production and thermal exchanges with the environment.

This can be summarized by the following equation (1):

$$\pm S = M - (\pm W) \pm K \pm C \pm R \pm E$$

where S = body heat storage

M = internal heat production or energy metabolism

W = mechanical work

K = conductive heat exchange

C = convective heat exchange

R = radiative heat exchange

E = evaporative heat exchange

S can be considered as a key parameter to evaluate the thermal stress induced

M is a function of the subject metabolism and activity

W usually represents rather small values for pilot's applications

The main issue is to model the different forms of heat exchanges which take place between the body and the environment.

## ATHOM COMPUTER MODEL

DASSAULT AVIATION developed a computer program named ATHOM (which stands for Analyse Thermique de l'HOMme), modeling human thermal behavior, compatible with applications for pilots.

It consists in a 162 node human model, made of 14 segments, each being composed of 4 compartments :

1. Core
2. Muscle
3. Fat
4. Skin

from inside to outside, as pictured below:

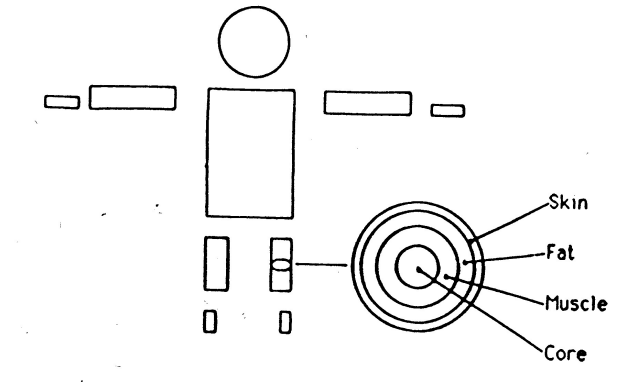


Figure 1 : Human thermal model structure

The head segment is spherical. The trunk and limbs segments are cylindrical except the hands and feet which are rectangular.

The dimensions of the segments are functions of the stature, weight and fat rate of the subject.

This leads to  $14 \times 4 = 56$  compartments, each of them being represented by a node.

The heat exchanges within the body involves partly the blood loop which is taken into account in the model through supplementary nodes as pictured below

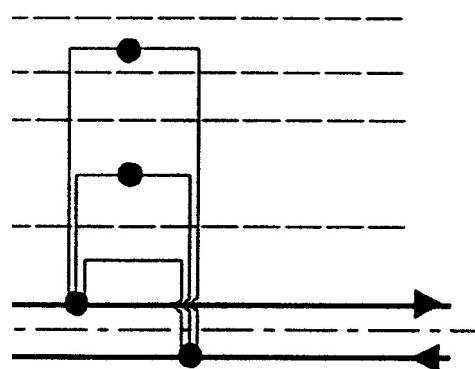


Figure 2 : Blood loop and nodes

Fifty additional nodes are involved in the blood loop.

The link with the environment goes through clothing which adds 14 extra nodes (each facing a segment of the model).

Finally, the external environment is represented by 3 x 14 limit nodes (corresponding to the 14 segments with respect to the three modes of exchanges at this level: conductive, convective and radiative).

The couplings in terms of coefficients of exchange are then calculated from the standard conductive, convective, radiative and evaporative formula, involving mainly differences of temperature (1).

Modeling the heat and mass transfers with the environment has been achieved with the help of a study conducted with NASA and NRC (2) which compared cases in normal and microgravity, normal and hypobaric conditions.

The ATHOM computer model also features:

- the computation of the metabolic activity of each compartment from the input of the overall metabolic activity
- a control system computing the blood flow, the sweating rate and the shivering process from the data of calculated skin and head core (hypothalamus) temperatures.
- the impact of the respiratory thermal exchanges as a function of the metabolic activity
- the impact of the posture of the subject (change of the heat exchanges between sitting and standing postures)

All in all, the general **inputs** of the program can be listed as follows:

#### Mission parameters

Metabolic activity  
Time duration

Posture of the subject

#### Environmental parameters

Type of ambient gas  
Ambiant pressure  
and for each segment:  
Dry temperature  
Radiative temperature  
Relative humidity  
Air speed and direction

#### Clothing parameters

For each segment  
Surface  
Weight  
Reflectance parameter  
Resistance to heat transfer  
Resistance to mass transfer

#### Subject parameters

Stature  
Weight  
Age  
Acclimatization

The **outputs** consist in:

- all compartment temperatures from which most interesting are usually skin and trunk core temperature
- heat storages
- sweat rates

The transfer function between inputs and outputs has been compared with experimental data in order to validate the model. This has been achieved in aircraft cockpits for moderately hot conditions on ground in South France in the summer. The results gave satisfactory matches (see figure 3).

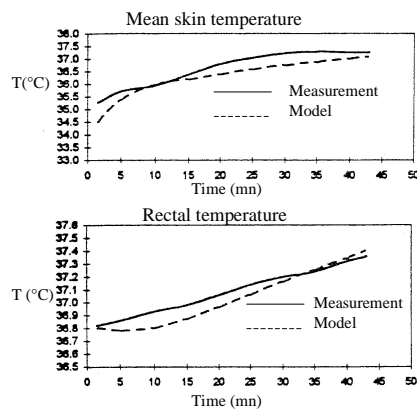


Figure 3: Comparison Model/ Experiments

The use of the program then requires evaluation criteria enabling the user to assess the criticality of a thermal global system (climate, Environmental Control System, clothing) for a specific population.

## THERMAL EVALUATION CRITERIA

The identification of evaluation criteria is difficult as it involves a subjective part. Moreover, parameters more varied than the subject parameters listed in the previous chapter are likely to be involved (motivation, endurance, experience, influence of the type of mission...).

It is very tricky to expand the analysis to such fields partly because data is lacking.

At this stage, we have focused the analysis on physiological parameters which is believed to explain a very important part of the variability in thermal stress and comfort, namely:

Core temperature: 37.5°C (limit of comfort); 37.7°C (impact on pilot's performance)

Mean skin temperature : 35.5°C (limit of comfort)

Heat storage: 120 kJ/m<sup>2</sup> (limit of comfort), 167 kJ/m<sup>2</sup> (safety limit), 210 kJ/m<sup>2</sup> (impact on psychomotive tasks), 334 kJ/m<sup>2</sup> (danger)

Temperature gradients within the skin surface should also be limited. We consider today a 3°C maximum difference between the mean skin temperatures of the head and torso. Moreover, mean skin temperature differences between segments should not exceed 8°C.

These criteria must be considered carefully; these points can be widely discussed and there is no general convergence especially on the quantitative levels.

Sweating is not involved in the criteria as it cannot be considered as a purely negative parameter. Evaporation of sweating is a powerful means to release heat storage, but it is then very important to compensate body loss by adequate provision (drinking...).

The computer does not account for very local phenomena possibly entailing local sweating for example (heavy pockets...).

Concerning the criteria, temperature time gradients are likely to cause thermal comfort degradation or more severe consequences. Unfortunately, data seems to lack on this point and it would be useful to collect such informations, especially in the case of sudden decrease in temperature.

## APPLICATIONS TO PILOTS CASES

The computer model has been run for pilots cases. Looking back at the inputs of the model, the following data have been considered:

Mission parameters

It is very important to take the pre-flight phases into account, not only the waiting phase before take-off but also the walking and installation phase on-board. Metabolic activity can be high in these phases and this can influence flight data greatly.

Scenarios are usually run starting from the end of briefing phase which is supposed to take place in an air-conditioned room.

### Environmental parameters

This data is identified for all pre-flight and flight phases.

Outside climate data is found in tables, especially for critical climates (very hot and humid, hot and very humid, with heavy solar radiation).

Cockpit data are extracted from Environmental Control System data. Air velocities and radiative temperatures come from experimental measures. The ( $Q_{\text{flow}}$ ,  $T_{\text{inlet}}$ ) values are highly influent on the results.

### Clothing parameters

These data are measured or given by manufacturers. Resistance to heat and mass transfers are especially important and slight variations (10%...) of these parameters can be detected in the results.

### Subject parameters

It is very important to accommodate a maximum percentage of pilots. This means varying the parameters (stature, weight, fat percentage, age, acclimatization) while taking adequate variances and correlations into account. Significant differences have been obtained within the population: for example, up to 30% of variation in final heat storage after two hours in hot climate. Therefore, it is important to pick up critical profiles for analysis.

### Example of results

The following figure shows typical results for core temperature and heat storage all over a 120 minute mission.

The initial increase corresponds to the pre-flight phases (walking, installation on-board, waiting phases).

The decrease takes place after take-off when the Environmental Control System offers more cooling.

The next increase corresponds to a flight phase at low altitude and very high speed.

The last decrease is the final phase of the flight at lower speeds.

It is important to notice the great impact of the phases before take-off and it appears important to decrease thermal stress during these phases (reduce metabolic rate, shelter against solar radiative constraints...).

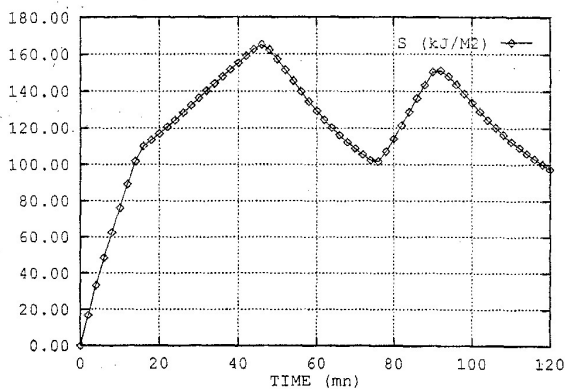
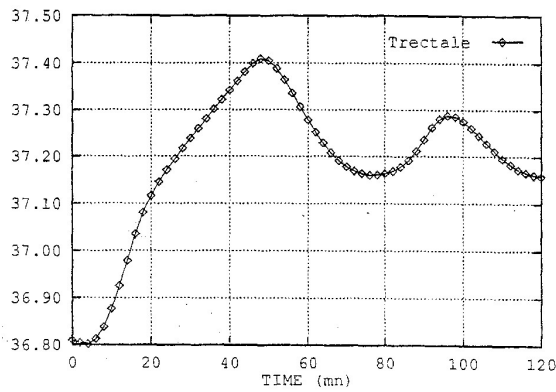


Figure 4 : Pre-flight / flight results

From these data, it is possible to quantify solutions (for example, the slope of the heat storage curve can be related to the cooling power which should be considered in this particular case).

## CONCLUSION

This paper has presented a modeling tool named ATHOM developed by Dassault Aviation so as to improve pilots performance and comfort with respect to thermal stress.

It is centered on a numerical representation of the thermal behavior of the human body. It consists in a 162 node model taking the thermal exchanges between the body, the clothing and the environment into account.

Its application to pilots cases shows the great impact of the pre-flight phases. This model is currently used

- to assess existing designs in extreme thermal conditions,
- to have a feedback concerning the thermal performances of pilots clothing
- to improve air circulation (Environmental Control System).

## REFERENCES

1. Handbook of Human Factors and Ergonomics. Second Edition. Edited by Gavriel Salvendy. John Wiley and Sons, Inc.
2. SAE Technical Paper n° 941318. Heat Transfer and Mass Transfer in Microgravity and Hypobaric Environments. X. Chalandon (Dassault Aviation), B. Webbon (NASA), L. Montgomery (NRC). 1994.

