APOLLO SYSTEMS DEPARTMENT

GENERAL ELECTRIC

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SUBJECT

The Application of MINIQUASI to Thermal Program Boundary and Initial Value Problems

(NASA-CR-160227) THE APPLICATION OF MINIQUASI TO THERMAL PROGRAM BOUNDARY AND INITIAL VALUE PROBLEMS (General Electric Co.) 8 p HC A02/MF A01 CSCL 06P

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This study investigates the feasibility of applying the solution techniques of MIniquasi to the set of equations which govern the thermoregulatory model of Stolwijk. For solving nonlinear equations and/or boundary conditions, a Taylor Series expansion is required for linearization of both equations and boundary conditions. The solutions are iterative and in each iteration, a problem like the linear case is solved. It will be shown that Miniquasi cannot be applied to the thermoregulatory model of Stolwijk as originally planned.

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ASD 4028

PROGRAM DESCRIPTION GUIDE

A. IDENTIFICATION

Program Name - MINIQUASI and the Thermoregulatory Model of Stolwijk

Programmer's Name - V. J. Marks

Date of Issue - September 20, 1974

B. GENERAL DESCRIPTION

This study will investigate the feasibility of applying the solution techniques of Miniquasi to the set of equations which govern the thermoregulatory model of Stolwijk. For solving nonlinear equations and/or boundary conditions, a Taylor Series expansion is required for linearization of both equations and boundary conditions. The solutions are iterative and in each iteration, a problem like the linear case is solved. It will be shown that Miniquasi cannot be applied to the thermoregulatory model of Stolwijk as originally planned.

C. USAGE AND RESTRICTIONS

Machine and Compiler Required - Xerox Sigma 3
- ANSI FORTRAN

Peripheral Equipment Required - Card Reader and Line Printer

Approximate Amount of Memory Required - 1382 hexidecimal (5043 decimal)

D. PARTICULAR DESCRIPTION

Equations Used and Derivations - See References 1 and 2

Definitions of Terms Used - See Reference Set of 1 - Appendix A and B

The Miniquasi program is designed to provide numerical solution of multipoint boundary value problems governed by a system of up to 20 first-order ordinary differential equations. This system of equations may have up to 20 boundary conditions. The equations must be written and programmed in their linearized form for purposes of applying Miniquasi. The equations which describe the controlled system of the thermoregulatory model are given below with temperature as the dependent variable T.

T(i)	Temperature of the i^{th} element, ^{o}F.
t	Time, Hours
VPDEW	Vapor Pressure at Cabin Temperature, mm Hg

C(i)	Specific Heat * Mass, BTU/$^{\circ}$F
P	Cabin Pressure, PSI
TCAB	Cabin Temperature, $^{\circ}$F
TUG(i)	Temperature of Garments, $^{\circ}$F
TW	Temperature of the Cabin Wall, $^{\circ}$F
CLO	Ratio of Clothed Area to Total Area
RM	Metabolic Rate, BTU/Hr.
QB(i)	Basal Metabolic Rate, BTU/Hr.
UEFF	Useful Work Efficiency, %
AC	Total Convective Area, Ft^{2}
AR	Total Radiative Area, Ft.^{2}
VCAB	Cabin Free Stream Velocity, CFM
VEFF	Cabin Ventilation Efficiency, %
G	Gravity (Normal to Earth)
CLOV	Clothing Thermal Resistance, Hr. Ft.^{2} $^{\circ}$F/BTU
EUG	Emissivity of Undergarment
CPG	Specific Heat of Gas, BTU/lb. $^{\circ}$F

The thermoregulatory model contains 41 nodes composed of the core, muscle, fat, and skin for the ten geometric compartments of the head, trunk, arms, legs, hands, and feet. The forty-first node is the central blood pool. The equations of the heat balance in these compartments are of the basic form.

$$\text{Mass} * Cp * \frac{dT}{dt} = \Delta Q \qquad (1)$$

Where ΔQ represents the heat loss or heat production terms associated with each of the forty-one nodes. The terms include conduction to adjacent nodes, convection to the blood, radiation terms, and the sensible and latent heats of vaporization from both the skin and the lungs. The many assumptions necessary to derive the heat flow terms from physical laws and geometry can be found in References 2 and 3.

It is the heat terms when expanded into functions of only independent variables which are nonlinear and are not amenable to the linearization techniques suggested in Miniquasi. These equations in their expanded form become:

Temperature of the Head Core = T(1)

$$\frac{dT(1)}{dt} = \frac{1}{C(1)} * \Big[QMET(1) + QCONV(1) - QRLAT1 - QCOND(1) - QRSEN(1) \Big] \tag{2}$$

where these terms are from

QMET(i)	Metabolic heat produced in the i^{th} element.
QCONV(i)	Heat exchanged due to convection between blood and tissue in the i^{th} element.
QRLAT1	The component of latent heat loss from the lungs which is distributed to the head core.
QCOND(i)	The heat exchanged with adjacent tissue compartments due to conduction in the i^{th} element.
QRSEN(i)	The sensible heat losses from the lungs which are distributed to the i^{th} element.

In expanded form:

$$QMET(1) = QB(1) = (CONSTANT) \tag{3}$$

$$QCONV(1) = BF(1) * (T(41) - T(1)) \tag{4}$$

where

BF(1) is the blood flow rate in the compartment, and

$$BF(1) = 99.3 \text{ lb/hr.} \tag{5}$$

$$QRLAT1 = \frac{0.386 * 0.0415 * PCAB * 144.0}{51.5 * (TCAB + 460.)} * \Big[1.0 - .33 * (14.7 - PCAB)\Big] * RM * \frac{0.622 * 0.8 * VPT\ (TEXP)}{PCAB - 0.8\ VPT\ (TEXP)} - 0.622 * \frac{0.622 * VPT(TCAB)}{VCAB - VPT(TCAB)} \tag{6}$$

where

$$TEXP = 86.9 + 0.066 * TCAB + 57.4 * \frac{0.622\ VPT(TCAB)}{PCAB - VPT(TCAB)} \tag{7}$$

and VPT is the functional relationship between temperature and vapor pressure.

$$VPT(TEXP) = 3207.0 * 10^{\beta}$$

where $\beta = \frac{1.8*647.27-(TEXP+460)}{TEXP + 460} * 3.244 + .005868$

$$* \left(647.27 - \frac{(TEXP + 460)}{1.8}\right) + (1.17 * 10^{-8}) * \left(647.27 - \frac{(TEXP + 460)}{1.8}\right)^3 \tag{8}$$

$$QCOND(1) = 3.04 * (T(1) - T(2)) \tag{9}$$

$$QRSEN1 = \frac{.385 * .0418 \qquad * PCAB * 144.0 * RM * CPG}{48.3 * (TCAB + 460)}$$

$$*((0.385*T(1) + 0.086 * T(2) + 0.0287 * T(3) + 0.238 * T(5)$$

$$+ 0.2615 * T(6)) - TCAB) * (1.0 - 0.33 * (14.7 - PCAB)) \tag{10}$$

The remaining core temperatures (nodes 5, 9, 13, 17, 21, 25, 29, 33, 37) are computed by similar equations.

The muscle compartments introduce a set of nonlinearities in the blood flow calculations and metabolic heat generated with the shivering equations and blood flow regulations. In the example of the trunk muscle:

$$QMET\ (6) = QB\ (6) + 0.3 * (UEFF * (RM-QB)) + 0.85 * QSHIV \tag{11}$$

where

$$QSHIV = (-50881.0 + 1928.6\ TC + 61.4\ TC^2$$

$$+T(42) * (4453.4 - 168.5\ TC + 5.37\ TC^2)$$

$$+T(42)^2 * (-106.97 + 4.05\ TC - 1.89\ TC^2)) * 3.6 * 3.97 \tag{12}$$

and TC is $(T(1) - 32) * \frac{5}{9}$

$$QCONV(6) = BF(6) * (T(41) - T(6)) \tag{13}$$

where $BF(6) = 13.2 + \frac{0.3 * (1.0-UEFF * (RM-QBASAL))}{1.3} + 0.85 * QSHIV$ (14)

The elements of the skin have some additonal heat exchange terms as given in the heat balance for the skin of the trunk.

$$\frac{dT(8)}{dt} = \frac{1}{C(8)} *(QMET(8) + QCOND(7) - QCONV(8) - QRAD(8) - QSEN(8) - QLAT(8)) \tag{15}$$

where

QRAD(i) The heat loss due to radiation distribution to the i^{th} element.

QSEN(i) The sensible heat loss due to evaporization of sweat in the i^{th} element.

QLAT(i) The latent heat loss due to evaporization of sweat on the i^{th} element.

The skin elements also add to the complexity of the linearization process due to radiation terms based on Stephan's Law:

$$Q = AR*\sigma* (T^4_{skin} - T^4_{wall}) \tag{16}$$

where σ is the emissivity of the skin with logic for including the garments; the equation for radiative heat exchange for the skin of the trunk becomes:

$$QRAD(8) = HR * (TUG(8) - TW) \tag{17}$$

where

$$HR = \sigma * AR(8) * EUG((TUG(8) + 460)^3 + (TUG(8) + 460)^2 * (TW + 460) + (TUG(8) + 460) * (TW + 460)^2 + (TW + 460)^3) \tag{18}$$

where

$$TUG(I) = \frac{HR * TW + HC * TCAB + \frac{AC(8)}{CLO} * T(8)}{HR + HC + \frac{AC(8)}{CLO}} \tag{19}$$

HC is the convective heat losses from the skin.

$$HC = 0.026 * AC * (PCAB * VCAB)^{0.5} \tag{20}$$

or

$$HC = 0.06 * AC * (PCAB^2 * G * \left|TUG(8) - TCAB\right|)^{0.25} \tag{21}$$

whichever is greater.

The resulting first-order differential equation of degree 4 contains eight variables of state. Further difficulties are found when considering the blood flow rates and the production and evaporization of sweat to these compartments. The final equations can be found in Reference 3 and again constitute nonlinearities of the controlled system which are necessary to represent the thermoregulatory system. This set of 42 equations for the controlled system includes nonlinearities which do not allow a valid Taylor Series expansion, since these equations cannot be expressed as a power series, $\sum_{M=0}^{\infty} C_M (X-A)^M$ (see Reference 4). Therefore, the equations of the thermoregulatory model are not amenable to the linearization methods found in Miniquasi.

In conclusion, it has been found that the methods used in MINIQUASI cannot be applied to the complex equations of the thermoregulatory model. If somehow these nonlinearities could be removed, the resulting equations would, most likely, no longer accurately represent the physical processes of heat flow in the human body.

REFERENCES

1. Childs, Bart, et al. , "QUASI - Solution of Multipoint Boundary Value Problems of Quasilinear Differential Equations", University of Houston RE7-69, September 1969.

2. "41-Node Transient Metabolic Man Program", LEC/672-23-030031, Lockheed Electronics Company, Houston Aerospace Systems Division.

3. "Simplification of 1108 Lockheed Version of Stolwijk Model and Incorporation of Improved Convective Heat Transfer Coefficient", TIR 750-MED-2002, General Electric Company, Space Division, Houston Programs. Also, see revision TIR 750-MED-2004.

4. Kreysig, Erwin, Advanced Engineering Mathematics, Second Ed.,Wiley & Sons, New York, 1962. pp. 155-165.