The Optimum Design of Personal Liquid Cooling System

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ABSTRACT

Personal liquid cooling system is an effective means of reducing heat stress when pilots wait in hot aircraft cockpits and operate at a high speed and a low altitude. The liquid cooling system includes water cooled suit and heat sink. Its optimum design method is presented in this paper, i.e. with the computer-aided design, the system's power consumption, cooling effect and size match well to fit the need of heat removal in practical flight.

The optimum result is compared with available liquid cooling system which has been tested by field trial flight in our country. Finally, the integration of water cooled suits with other protective suits is considered.

I. INTRODUCTION

In morden flight, it is unavoidable for pilots to operate in hot aircraft cockpits. The water cooled suit(WCS), with the circulation of cold water supplied by heat sink, makes a relatively cold microclimate around human body and takes away both metabolic and external heat to reduce heat stress.

The available heat sinks include vapor compression refrigeration system, thermoelectric cooler and water-ice cooler, their performance data are listed in table 1. The field trial flights by our Air Force show that they can work normally in aircraft without bad effects on the performance of aircraft.

It is the water cooled suit that connects human and heat sink. Its interaction between the conditioned human and the conditioning apparatus is important in the liquid cooling system optimum design, for the performance parameters of suit will affect both the heat sink and human being.

II. THE PROPOSAL OF OPTIMUM DESIGN CRITERION

The first water cooled suit was developed in 1962. During the recent three decades, people have developed different types of WCS and tested their thermo-physiological characteristics. But little attention have been focused on their comparison, there is yet no optimum design criterion of WCS that can be widely accepted.

Theoretical analysis shows that the WCS cooling capacity(Q) is direct proportion to the temperature difference between skin(Ts) and inlet water(Tin) and an exponential function of water flow rate(m), which can be written:

$$Q = mCp[\ 1-\exp(\ -UA/mCp\ )\ ](\ Ts-Tin\ ) \qquad (1)$$

where U is the overall heat transfer coefficient between skin and water ($w/m^2 \cdot ℃$),

A is the total wetting area of water, when tubes are used,

$A = \pi \cdot Din \cdot L \cdot N(\ m^2\ )$

Din __ tube diameter(m)

L __ single tube length(m)

N __ number of parallel tubesall tubes

Table 1. AVAILABLE HEAT SINKS' PERFORMANCE DATA

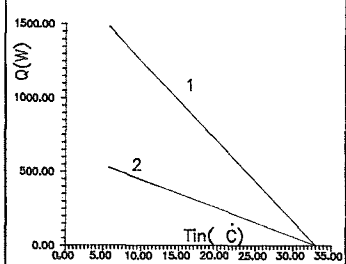
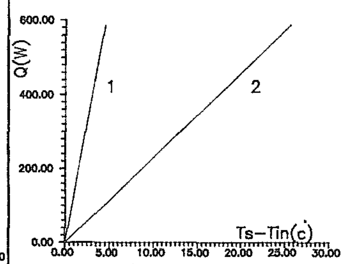
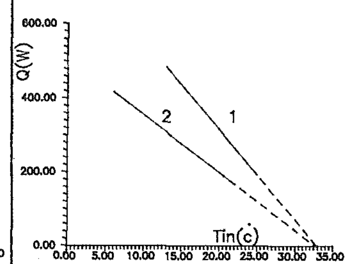
type	water-ice cooler	thermoelectric cooler	vapor refrigeration system(D.C.)	vapor refrigration system(A.C.)
cooling capacity(w)	90	120	200	600
input power (w)		120	150	400
power supply	12V dry cell	direct current	28V(12V)	220V
weight(kg)	5	10	15	30
duration	one hour	continuous service	continuous service	continuous service
application	portable situation eg. steel worker fireman	aircraft automobile	aircraft automobile	hospital laboratory

Cp is the specific heat of water (KJ/Kg · ℃)

The parameters of WCS are divided into two groups: controllable parameters(Tin) and uncontrollable parameters(m, Cp, U and A).

See three results done by previous researchers, each group has identical values of mCp.

Table 2. COMPARISON BETWEEN DIFFERENT WCS

researcher		D.R. Burton[1]	W. Elkins[2]	M.H. Harrion[3]
Q~(Ts-Tin) figure				
note	1	potential cooling capacity	New WCS	120 meter suits
	2	actual cooling capacity	Apollo WCS	60 meter suits
formula	1	Q=54.3(33-Tin) (w)	Q=131.9(31.1-Tin) (w)	Q=24.3(32.9-Tin) (w)
	2	Q=19.3(33-Tin) (w)	Q=23.0(31.1-Tin) (w)	Q=15.6(32.7-Tin) (w)

From the chart, we find out that all WCS Q~(Ts-Tin) lines have a common vertex(Tin≈33, Q=0), with different slopes. It can be explained that the water cooled suits have similar operational characteristics at thermal neutrality, and when supplying the same cooling rate, the better WCS is, the higher Tin can be used. To the human body, it can avoid the discomfort caused by partial vasoconstriction and reduce heat gain from the environment. To the design of heat sink,the COP(coefficient of performance) can be improved and smaller heat transfer area is needed for the higher temperature difference between WCS water and refrigerant.

Their mathematical formula is:

$$Q = \lambda (Ts - Tin) \qquad (2)$$

λ is a recombination coefficient which means under a certain condition, Tin decreases 1℃, the cooling rate of WCS will increase λ (w).

From the previous analysis, the optimum criterion can be put forward: under the same input power of water pump(Npump) , the higher λ is, the better WCS performance is, resulting in the more economic energy comsumption. The reason for identical Npump is: in comparison situation, it is much easier to get the same Npump than the same m or the total wetted area of the tubes in the suit(A).

III. COMPUTER OPTIMUM DESIGN

From the equations (1) and (2), we can express λ as:

$$\lambda = mCp[1 - \exp(-UA/mCp)] \qquad (3)$$

It shows that λ increases with A, m and U, but m and A will be restricted by many other factors.

The computer program is to choose the optimum parameters to get the maximum λ. It synthesizes heat transfer theory, pump performance curves, human body physiological model and restriction of suit dimension and material.The program flow chart is shown in Fig.1.

The program lays little emphasis on the clothing insulation worn over the WCS and the environmental conditions, for in comparative studies these factors will be canceled out each other.

Table 3 gives an example of the optimum result for water cooled vest(WCV) in which cold water is circulated in thin PVC tubes.

Table 4 gives the comparison of the newly designed vest according to the optimum result with the previous one which has been used in trial flight. Their computer λ values are given.

IV. EXPERIMENTAL VERIFICATION

The experiment's aim is to verify the computer program's correctness and compare the Q~(Ts- Tin) figure of two vests.

The test was done in a hot automobile(D.B.

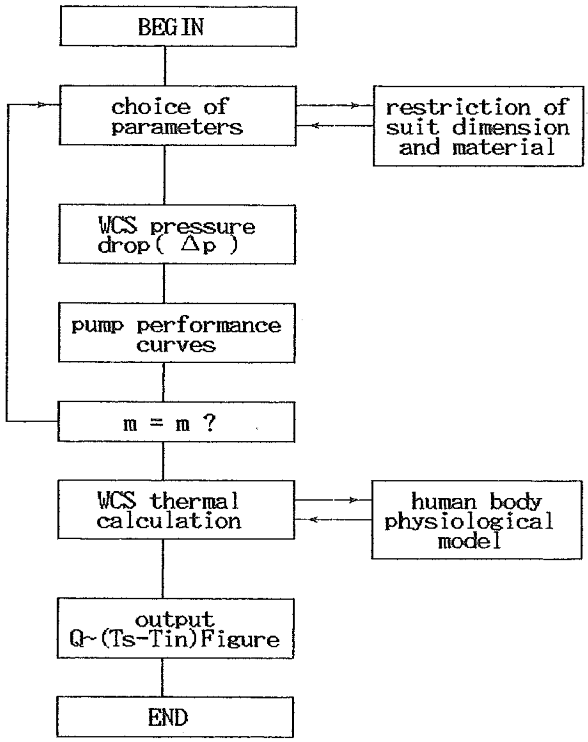


Fig.1 THE PROGRAM FLOW CHART

40℃~50℃), simulating the summer environment. Three healthy undergraduate volunteers took part in the test. They could control the WCV inlet water temperature.Cold water was supplied by newly developed water-ice cooler, pump's input power was 4.5w.

Through measurement of WCV Tin, Tout and Ts etc., we can get their cooling rate Q:

$$Q = mCp(Tout - Tin) \quad (4)$$

The thermal data were inputed into computer and regressed by GRAPHER software.

At last the pressure drops and clothes weights of the two vest were measured,as listed in table 5.

After experiments, the undergraduates complained that although the previous vest was tailored very small in order to maintain intimate tube comtact with the body, the front was not snug yet, the back was much better. So they felt colder in the back and warmer in the front. The newly developed WCV can overcome these disadvantages, it elastically and closely fits several body sizes and equally cools them. The measurements of pressure drop and clothes weight show that the values of the new vest are slightly less than the previous one.

V. ANALYSIS

Analysis of experimental data indicates that the λ value of a certain WCS will not change

Table 3. OPTIMUM RESULTS FOR WCV

UNCONTROLLABLE PARAMETER	INTERPRETATION	OPTIMUM RESULTS
U(W/m²℃)	U is the main factor affecting λ, it can be improved by fiiting well	adopting reticular formation to braid tube network
m(kg/h)	a suit corresponds to a suitable m	about 3(UA)/Cp
Npump(w)	a centrifugal pump, light weight, size Φ30×65mm	3 ~ 5
pipe work distribution	to vest, it has little affection on λ, so equally distribute the tubes to avoid partial overcooling	back→shoulder →front →shoulder →back
Din/Dout (mm)	In the range of 1.5~3 mm, the larger Din is favourable	3/4
N	N has affection on pressure drop and suit structure	10
L(m)	limited by pressure drop and suit structure	3.2
total length of tubes S (m)	L×N	32

with mean skin temperature. The phenomenon can be explained as the following:

From eq.(2) and eq.(4), λ can be written as:

$$\lambda = mCp(Tout - Tin)/(Ts - Tin) \quad (5)$$

or

$$\lambda = mCp \cdot e$$

$$e = (Tout - Tin)/(Ts - Tin)$$

where e is the effectiveness of WCS. As a heat exchanger working in a normal state, the effectiveness of WCS will not change,so that λ will be constant to a certain WCS, that is necessary in the proposal of optimum design criterion.

The computer calculation results coincide with the experimental data.Their vertices of Q~(Ts-Tin) lines may deviate from the original point for heat gain from the environment.

VI. SUMMARY

The water cooled suit plays an important role in the liquid cooling system. The proposal of λ as an criterion of WCS optimum design and a scale to compare the advantages or disadvantages between different suits' performance has preliminaryly been convinced but needs to be further studied.

The introduction of computer into the WCS design is a distinctive feature in this research work, which can effectively avoid design and test aimlessly.

Table 4. STRUCTURE COMPARISON BETWEEN TWO VESTS

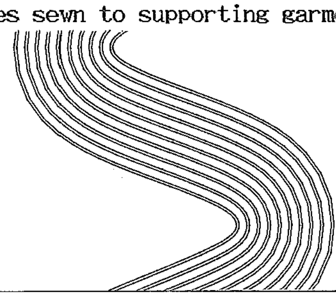
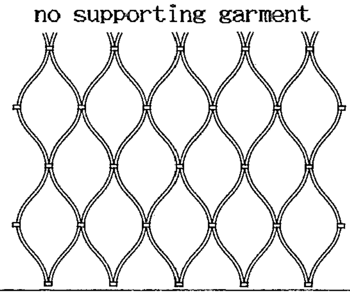
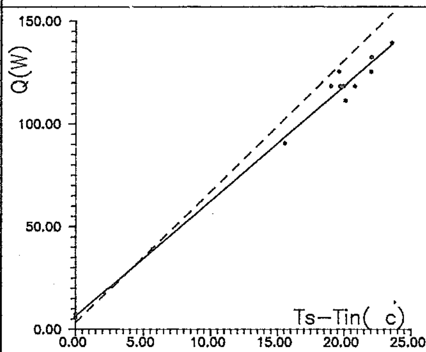
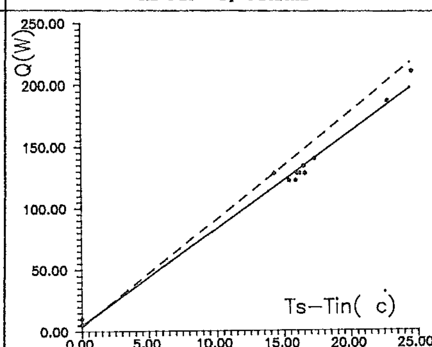
structure comparison	before optimum	after optimum
Din/Dout (mm)	2.4/3.2	3/4
N	20	10
S(m)	40	32
A(m^2)	0.3	0.3
tube distribution	back→shoulder →front	back→shoulder →front →shoulder →back
tube fixation	tubes sewn to supporting garment 	no supporting garment 
Npump(w)	4.5	4.5
λ (w/℃)	6.39	8.68

Table 5. EXPERIMENTAL COMPARISON BETWEEN TWO VESTS

	before optimum	after optimum
Q~(Ts-Tin) Figure	 --- calculation ___ test	 --- calculation ___ test
Δp (KPa)	10.86	9.86
vest weight (with water)	800g	700g

The reticular formation used to braid the WCS tubes is progressive than the previous construation.The newly developed sutis not only overcome the stiff impression but also need no supporting garments. The tube assembly is an independent suit by themselves. Thus, the WCS tube assembly can be fastened under other protective clothes at a few points. The integration of WCS with other suits will make liquid cooling system more acceptable by pilots.

REFERENCES

[1] Burton, D.R.; Engineering Aspects of Personal Conditioning; AD694130, pp.33-49.

[2] Elkins, W.; Advanced High Efficient Liquid Transport Garment; AIAA 73-1334.

[3] Harrion, M.H.; Operational Characteristics of Liquid Conditioned Suits; ASEM. 1978, 49(8):994-1003.