Liquid Conditioned Suit and its Use in Alleviating Heat Stress in Military Flying

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Abstract

EFFECTIVITY of two models of liquid conditioning unit, indigenously developed, was evaluated on the basis of the reduction in physiological thermal strain in subjects exposed to simulated heat stress.

Model-1, a laboratory model based on Freon cooling was found to produce 48% reduction in heat accumulation and 75% reduction in the rise in heart rate for 30 min exposure to 50°C DB with 50% relative humidity, as compared to their respective levels reached during trials conducted without the liquid cooling.

Model-2, a miniaturized insulated ice pack, was found to offer more cooling, as judged from the thermal strain responses of the subjects in a 60 min exposure to the same thermal environment. Percentage reduction in thermal strain, as reflected in the comparative analysis of the mean values of heat accumulation and rise in heart rate at 60 min of exposure with and without the use of this liquid conditioning system, was found to be 70%. At a relatively lesser degree of thermal stress situation viz. 50°C DB with 30% relative humidity, cooling provided by this pack was found to be sufficient in maintaining a virtual thermal comfort for one hour exposure. Miniaturization attained in this model provides a chance for its use in modern military aircraft.

Introduction

Low level flying in tropical summer results in high temperature within the cockpit. A few in-flight studies (2,5,8,10) demonstrated that the cockpit temperatures often shoot to 50°C and above, indicating that the aircooling systems in fighter aircraft are grossly inadequate to ensure thermal comfort to aircrew. In view of the accepted need to minimise the weight and power penalty in fighter aircraft, thus limiting the use of higher capacity air conditioning systems in them, the present day thinking in mitigating the thermal stress of the cabin atmosphere is by means of cooling the microclimate between the skin and the inner layer of the clothing.

Out of the two accepted modes of microclimate cooling, viz. by air ventilated suit (AVS) and by liquid conditioned suit (LCS), the latter has been considered to be superior due to the higher heat extraction capacity of liquid to air, which results in a power advantage for the LCS system compared to the AVS system (1).

Earlier laboratory studies (3,4,6,9,11) with various designs of the suit and with varied materials used as coolants met with gratifying results. Various cooling systems, viz. freon package, liquid oxygen, solid carbon dioxide snow and water ice have been investigated for their possible use. Efforts are now being made to develop a suitable cooling pack which will be compatible with the space, weight and power provision of the existing aircraft.

Two such systems, viz. Model-1, a laboratory

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model of freon package and Model-2, a miniaturized insulated ice package, have been developed in this Institute with the idea of studying their suitability in alleviating the heat load that is commonly prevalent in low level flying in tropical summer. The present study reports the effectivity of these two systems in terms of the reduction in physiological thermal strain.

Material and Methods

LCS Systems

Model-1: The first model of the refrigerant pack for laboratory trials on liquid conditioned suit derived its cooling from the conventional freon refrigeration. The LCS supply of water-glycol mixture was cooled by circulating it through the coils embedded in the cooling chamber of the refrigeration unit. The fluid was circulated in the suit using a 1/40 HP water pump which gave a liquid circulation of 1.75 litres/min when the suit was connected to the system. The cooling chamber, which was well insulated, contained water and the water was made to freeze prior to the start of the experiments, by running the refrigeration unit for approximately 2 hours. Freezing was confirmed by noting the temperature of the chamber using a thermometer provided for the purpose.

Model-2: The second model derived its cooling from fusion of ice and gradual raising of temperature of water thus formed. Coils for circulating the liquid (water-glycol mixture) are embedded in a rectangular copper container of 8.5" x 4" x 4" dimension. The container could take two litres of water when it is filled up. After filling the container, a few ml of water is removed so as to cater expansion when ice is formed. The container can be introduced into an insulating box by sliding out the top lid of the box. Prior to the start of the experiments, the copper container is kept in a deep freeze so that its water turns into ice. It is then transferred to the insulating box and connected to the liquid conditioned suit. The system can provide about 200 Kcal of refigeration, which is considered adequate for most of the fighter/bomber flying based on the heat storage data available.

Subjects

In all, 9 healthy male volunteers participated in the study. Their age and physical characteristics are shown in Table-1.

TABLE 1

Age and physical characteristics of the subjects

Subject	Age (Yrs)	Height (Cms)	Body weight (Kgs)	B.S.A. (m^2)
SSN	31	174	51.0	1.60
PKB	32	178	63.0	1.78
EMI	35	170	66.5	1.76
DKB	27	165	58.0	1.62
DYR	40	163	66.0	1.70
MBD	36	172	65.0	1.75
CAV	46	162	51.5	1.52
RKS	32	167	60.0	1.66
MKV	33	167	75.0	1.83
Mean	34.7	168.7	61.8	1.69
± Sd	5.6	5.3	7.6	0.10

Simulated thermal environment

Two different thermal conditions were simulated in the laboratory Hot Cockpit.

Thermal condition 1: 50°C dry bulb and 39°C wet bulb temperature (relative humidity 50% with air velocity of 55 feet per min.)

Thermal condition 2: 50°C dry bulb and 32.5°C wet bulb temperature (relative humidity 30% with air velocity of 55 feet per min.)

Evaluation of LCS model 1 was made at thermal condition 1 only while LCS model-2 was evaluated in both the environments.

Clothing

Each subject was dressed in the following clothing:

(*a*) Cotton brief
(*b*) Liquid conditioned suit: type 2 series 5 Beaufort Air-Sea Equipment Ltd., U.K.
(*c*) Flying overall
(*d*) Nylon socks
(*e*) Shoes
(*f*) Type g inner helmet.

The control experiments were done without the LCS.

Experimental protocol

After weighing nude, the subject was instrumented for the measurements of skin temperature and heart rate and was dressed in the above mentioned clothing. After resting for about 15 min at room temperature, pre-exposure measurements of skin temperature, oral temperature and heart rate were made. The subject was then taken to the simulated environment of the Hot Cockpit. In studies with LCS model-1, subjects were exposed for 30 min and the physiological measurements were taken at 10,20 and 30 min of exposure. In studies with LCS model-2, the duration of heat exposure was 60 min and the measurements were made every 10 min. At the end of heat exposure, subjects were weighed nude to measure the sweat loss.

Physiological measurements

Skin temperatures were measured at the right chest wall, right upper arm, right upper leg and right calf with the help of thermocouples and read off on Ellab electrical thermometer. The mean skin temperature (MST) was calculated by giving appropriate weightage as recommended by Ramanathan (7). Oral temperature (OT) was measured with the help of a clinical thermometer. The mean body temperature (MBT) was calculated from MST and OT by the formula: MBT = 0.35 MST + 0.65 OT. Heart rate was measured from ECG tracings on a Grass model 5C polygraph. Sweat loss for the period of heat exposure was determined from the differences in nude body weight taken before and after the experiments with an Avery weighing scale which read up to an accuracy of ± 1 oz.

Suit inlet temperature

In LCS trials with Model-1, the suit inlet temperature was measured at 1, 10, 20 and 30 min of exposure with the help of a mercury thermometer inserted in a plastic T tube at a distance of 0.5 meter from the outlet point of the freon package.

Results

LCS trials with Model-1 vis-a-vis control trials

Thermal strain responses in terms of 30 min MST, OT, MBT, heart rate and the total sweat loss in control and LCS trials are shown in Table 2. The rise in heart rate and the heat accumulation for the same trials are shown in table 3. The cooling benefit of the LCS system, as envisaged from the percentage reduction in the rise in heart rate and the heat accumulation is also shown in the same table.

TABLE 3

Thermal protection offered by the Freon pack for 30 min exposure at 50°C DB and 39°C WB

Subject	Rise in heart rate (beats/min)			Heat accumulation (Kcal/m²)		
	Control	LCS	Diff	Control	LCS	Diff
SSN	36	6	– 30	57.1	21.7	– 35.4
PKB	30	18	– 12	67.1	27.5	– 39.8
EMI	46	10	– 36	78.7	28.9	– 49.8
DKB	28	6	– 22	63.0	35.1	– 27.9
DYR	28	2	– 26	58.0	47.0	– 11.0
MBD	44	10	– 34	41.0	29.6	– 11.4
Mean	35.3	8.7	– 26.6	60.8	31.6	– 29.2
± Sd	8.1	5.5	***	12.5	8.7	**
Cooling benefit			75%			48%

** $P < 0.01$ *** $P < 0.001$

LCS trials with Model-2 vis-a-vis control trials

Table 4 shows the thermal strain responses for 3 subjects at the 60th min of exposure at 50°C DB and 39°C WB in control and LCS trials with the Model-2. The rise in heart rate and the heat accumulation for the same trials and the percentage reduction offered by the LCS system are shown in Table 5.

TABLE 5

Thermal protection offered by the miniaturized ice pack for 1 hr. exposure at 50°C DB and 39°C WB

Subject	Rise in heart rate (beats/min)			Heat accumulation (Kcal/m²)		
	Control	LCS	Diff	Control	LCS	Diff
EMI	51	22	–29	82.5	36.4	–46.1
DYR	58	12	–46	82.2	17.7	–64.5
MKV	68	14	–54	99.6	25.5	–74.1
Mean	59.0	16.0	–43.0	88.1	26.5	–61.6
Cooling benefit			70%			70%

TABLE 2

Thermal strain responses at the end of 30 min exposure to 50°C DB and 39° C WB—Defferences between control and LCS trials with Freon pack

Subject	Terminal MST (°C)			Terminal OT (°C)			Terminal MBT (°C)			Terminal heart rate (beats/min)			Total sweat loss (gm)		
	Control	LCS	Diff	Control	LCS	Diff	Control	LCS	Diff	Control	LCS	Diff	Control	LCS	Diff
SSN	37.4	35.1	-2.3	37.9	37.0	-0.9	37.73	36.35	-1.38	120	68	-52	168	56	-112
PKB	37.5	35.8	-1.7	38.0	37.4	-0.6	37.84	36.86	-0.98	126	114	-12	308	196	-112
EMI	37.6	35.1	-2.5	38.2	37.1	-1.1	37.96	36.41	-1.55	120	88	-32	252	56	-196
DKB	37.4	35.7	-1.7	37.8	37.3	-0.5	37.68	36.70	-0.87	110	88	-22	280	168	-112
DYR	37.4	36.1	-1.3	37.4	37.2	-0.2	37.41	36.84	-0.57	120	94	-26	280	84	-196
MBD	36.9	35.7	-1.2	37.3	37.4	+0.1	37.20	36.84	-0.36	124	88	-36	364	140	-224
Mean	37.37	35.58	-1.78	37.77	37.23	-0.53	37.63	36.68	-0.95	120.0	90.0	-30.0	275	117	-158
± Sd	0.24	0.40	***	0.35	0.16	*	0.28	0.23	**	5.5	14.7	**	65	60	***

* P < 0.05 ** P < 0.01 *** P < 0.001

TABLE 4

Thermal strain responses at the end of 1 hr exposure to 50°C DB and 39°C WB—Differences between control and LCS trials with miniaturized ice pack

Subject	Terminal MST (°C)			Terminal OT (°C)			Terminal MBT (°C)			Terminal heart rate (beats/min)			Total sweat loss (gm)		
	Control	LCS	Diff	Control	LCS	Diff	Control	LCS	Diff	Control	LCS	Diff	Control	LCS	Diff
EMI	37.4	36.6	-0.8	37.8	37.5	-0.3	37.64	37.18	-0.46	117	100	-17	476	336	-140
MKV	38.4	36.5	-1.9	38.9	37.6	-1.3	38.76	37.21	-1.55	152	92	-60	644	336	-308
DYR	37.8	36.3	-1.5	38.0	37.2	-0.8	37.94	36.88	-1.06	164	100	-64	588	364	-224
Mean	37.87	36.47	-1.40	38.23	37.43	-0.80	38.11	37.09	-1.02	144.3	-97.3	-47.0	569	345	-224

TABLE 6

Thermal strain responses at the end of 1 hr exposure to 50°C DB and 32.5°C WB—Differences between control and LCS trials with miniaturized ice pack

Subject	Terminal MST (°C)			Terminal OT (°C)			Terminal MBT (°C)			Terminal heart rate (beats/min)			Total sweat loss (gm)		
	Control	LCS	Diff	Control	LCS	Diff	Control	LCS	Diff	Control	LCS	Diff	Control	LCS	Diff
EMI	37.2	35.5	−1.7	37.5	37.2	−0.3	37.38	36.61	−0.77	104	72	−32	450	170	−280
DYR	36.6	35.2	−1.4	37.3	37.1	−0.2	37.06	36.42	−0.64	104	76	−28	560	310	−250
MBD	37.3	35.7	−1.6	38.3	37.9	−0.3	37.85	37.14	−0.71	116	74	−42	840	365	−475
CAV	35.9	35.7	−1.2	37.3	37.2	−0.1	37.16	36.66	−0.50	90	80	−10	420	335	−85
RKS	37.2	35.6	−1.6	38.0	37.4	−0.6	37.71	36.78	−0.93	88	56	−32	450	110	−340
MKV	37.0	34.9	−2.1	37.8	37.3	−0.5	37.52	36.56	−0.96	108	80	−28	335	335	0
Mean	37.03	35.43	−1.60	37.68	37.35	−0.33	37.45	36.70	−0.75	101.7	73.0	−28.7	509	271	−238
±Sd	0.26	0.32	**	0.37	0.29	**	0.31	0.25	***	10.8	8.9	**	177	105	*

*P < 0.5   **P < 0.01   ***P < 0.001

Strain responses of 6 subjects at the end of one hour exposure to 50°C DB and 32.5°C WB for control vis-a-vis LCS trials with Model-2 are shown in Table 6. The rise in heart rate and the heat accumulation for these subjects at control and LCS trials and the corresponding reduction in strain by the LCS system are shown in Table 7.

TABLE 7

Thermal protection offered by the miniaturized ice pack for 1 hr. exposure at 50°C DB and 32.5°C WB

Subject	Rise in heart rate (beats/min)			Heat accumulation (Kcal/m²)		
	Control	LCS	Diff	Control	LCS	Diff
EMI	28	4	–24	45.2	25.7	–19.5
DYR	16	0	–16	27.1	11.3	–15.8
MBD	42	2	–40	37.0	24.4	–12.6
CAV	22	10	–12	40.2	22.5	–17.7
RKS	30	0	–30	46.2	27.0	–19.2
MKV	26	0	–26	55.1	6.8	–48.3
Mean	27.3	2.7	–24.6	41.8	19.6	–22.2
± Sd	8.8	3.9	**	9.5	8.4	**
Cooling benefit			90%			53%

** $P < 0.01$

Discussion

Model-1, the freon package, has been developed with a purpose of evaluating the effectivity of the cooling power of the system in a laboratory set up so as to use these results in the course of future development of a miniaturized field model.

The LCS inlet temperature as measured was sufficiently low at the beginning of heat exposure. With increased time, however, it was found to rise from its initial value of 18°C to reach 26.3°C at 30 min. This indicated that the refrigeration capacity of the unit was not matched with the heat load imposed. Inspite of this, there were significant reductions in the mean values of thermal strain parameters in LCS trials compared to those observed in control trials (Table 2). Cooling benefit of the system, as envisaged from the percentage reduction in the mean rise in heart rate for 30 min exposure at 50°C DB and 39°C WB in LCS trials vis-a-vis control trials, was found to be 75%. While the mean heat accumulation values were compared between the control and LCS trials, the percentage reduction in strain with the use of the LCS system was found to be 48% (Table 3).

An earlier study (6) with an ice cooled pack observed, a comparable reduction in heat accumulation for a similar heat exposure profile.

Considerable miniaturization and a high degree of insulation were achieved with the second model where ice was used as the refrigerant. With the amount of cooling provided by the latent heat of evaporation of 2 Kg. of ice, that was contained in the pack, it was found possible to maintain the subjects very much below the limits of tolerance for 60 min exposure to 50°C DB and 39°C WB (Table 4). With the use of this model, the rise in heart rate and the heat accumulation for 60 min exposure were only about 30% of those observed in control trials.

When the trials were conducted in a relatively less stressful environment of 50°C DB with 32.5°C WB, cooling offered by the miniaturized pack was found to be sufficient to maintain the subjects at a virtually comfortable state with hardly any rise in terminal heart rate and with only a slight increase in body heat storage.

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