

The influence of pressure on permeation efficiency factor for vapour transfer

T. Kozak and A. Majchrzycka

Technical University of Szczecin, The Faculty of Mechanical Engineering, Poland

Abstract

The paper reports theoretical development of the cloth permeation efficiency factor for vapour transfer F_{pcl} in the hyperbaric environment. Experimental investigations of F_{pcl} were carried out in the hyperbaric chamber in air within the total pressure range $p=0.1-5$ MPa. The study was undertaken to determine the effect of the total gas pressure on the cloth permeation efficiency factor for vapour transfer. The results of experiments demonstrated a large influence of the total pressure on F_{pcl} .

1 Introduction

Presented paper deals with the problem of thermal comfort inside the hyperbaric chamber, which is a typical experimental facility defined as a land-based, high pressure chamber which will accommodate divers at varying pressure to simulate the depth inside the chamber while the external pressure remains constant $p=0.1$ MPa. In order to determine the comfort temperature inside the hyperbaric chamber, the comfort equation was derived [1,2].

The comfort equation derived, based on the heat balance of the diver and basic thermal conditions allows to determine the comfort temperature as the function of the following principal variables: relative humidity of gas, mean radiant temperature, activity level of the diver, insulation value of the clothing, relative gas velocity, the composition and the total pressure of the breathing gas. The comfort equation is very useful both in designing and in operating the life support systems of hyperbaric facilities. The comfort temperature in the hyperbaric environment increases with the total pressure of gas and should be

maintained at a level higher ($t \cong 20\div 36^{\circ}\text{C}$) than that in normobaric air environment [1,2,3,4,5], while relative humidity should be kept within $\varphi = 0,4 \div 0,7$. The heat loss by evaporation of sweat from the surface of the skin is very important factor of thermoregulation in man. Vaporisation of sweat secreted on the skin is the principal outlet for man's heat loss necessary to maintain normal body temperature in a warmer environment. When subjects are clothed, mass-transfer theory becomes more complex. In the hyperbaric environment, poor evaporative rate [1,2,3,4,5,7,10] may induce in a diver feeling of high humidity (discomfort) and will prevent evaporative cooling of the skin. Essential for solving the hyperbaric comfort equation is to know the coefficient of sweat evaporation and permeation efficiency factor as the function of the total pressure and the kind of the breathing gas. The permeation efficiency factor F_{pci} describes „cooling efficiency of sweating on the skin surface for a clothed human body. The quantitative evaluation of permeation efficiency factor was discussed for normobaric environment in [6,7]. There are only a few papers concerning this subject in the hyperbaric environment [1,2,7,10]. The purpose of that paper is to develop relationship between the resistance of clothing to water vapour and its transfer from the sweating skin surface.

2.Theory

The evaporative heat loss for the unclothed human body can be calculated as:

$$\dot{Q}_e = m_w w r A D_u \quad (1)$$

As a simplification, let us imagine a still breathing gas layer of thickness δ_m surrounding the diver's skin, whose insulation is the same as the layer of the clothing δ_{cl} itself [6]. Assuming that this equivalent still gas layer has the same resistance to water vapour as the clothing itself, when it is transported from a surface at p_s to another surface at φp_{sw} . According to Stefan's Flow[1,6] in the absence of other potential gradients, the rate of diffusive vapour flow from the skin surface of temperature t_s , to the ambient gas at temperature can be calculated as:

$$m_w = \frac{D}{RT_s A \delta_m} (p_s - \varphi p_{sw}) \quad (2)$$

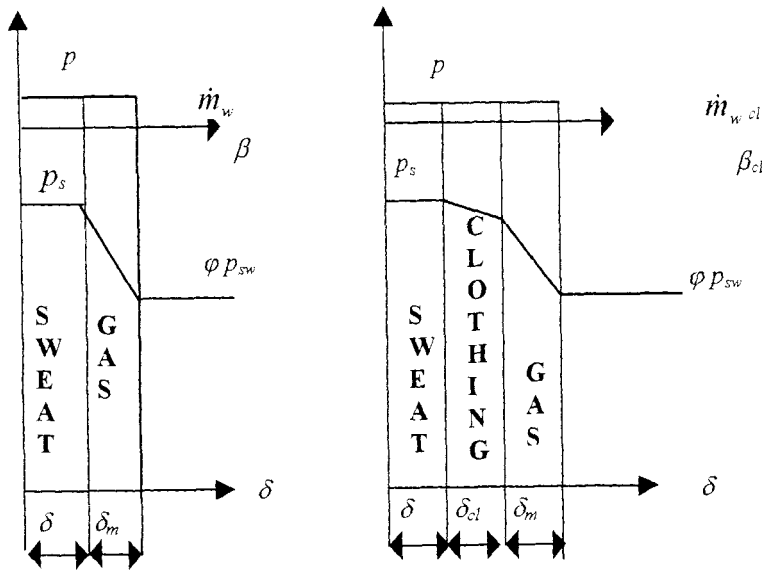


Figure1: Scheme of mass- transfer from: the naked skin and clothed skin,[1].

Introducing the sweat evaporation coefficient defined as:

$$\beta = \frac{D}{R_w T_s A \delta_m} = \frac{\beta_{w-m}}{p} \quad (3)$$

The sweat evaporation coefficient in the hyperbaric environment is the function of the total pressure, temperature, relative humidity and the composition of gas and can be written as:

$$\beta = f(p, t, \phi, x_i, v) \quad (4)$$

Resistance of the gas layer can be expressed as:

$$I_{dm} = \frac{1}{\beta} \quad (5)$$

Introducing eqn (3) and (4) to eqn (2) gives:

$$m_w = \beta (p_s - \phi p_{sw}) = \frac{(p_s - \phi p_{sw})}{I_{dm}} \quad (6)$$

For the case of vapour transfer from the skin surface through the clothing of the resistance I_{dcl} and the layer of the gas of the resistance I_{dm} the rate of diffusive vapour flow from the skin surface of temperature t_s , to the ambient gas at temperature can be calculated as:

$$m_{wcl} = \beta_{cl} (p_s - \phi p_{sw}) = \frac{(p_s - \phi p_{sw})}{I_{dcl} + I_{dm}} \quad (7)$$

$$I_{dm} + I_{dcl} = \frac{1}{\beta_{cl}} \quad (8)$$

The permeation efficiency factor F_{pcl} for water vapour transfer is defined [6] as the „cooling“ efficiency of sweating on the skin for a clothed human body. The permeation efficiency factor F_{pcl} can be written as follows:

$$F_{pcl} = \frac{I_{dm}}{I_{dcl} + I_{dm}} \quad (9)$$

Eqn (6) can be written as:

$$m_{wcl} = m_w F_{pcl} \quad (10)$$

Based on heat and mass transfer analogy it was assumed that the layer of the clothing makes decrease of the heat flux that is transferred by evaporation of sweat in the same proportion as mass transferred from the surface of the skin:

$$\frac{m_{wcl}}{m_w} = \frac{Q_{ecl}}{Q_e} = \frac{I_m}{I_m + I_{cl}} = \frac{I_{dm}}{I_{dm} + I_{dcl}} \quad (11)$$

Introducing into the eqn (11) heat transfer resistance I_m and I_{cl} developed in [1] gives:

$$F_{pcl} = \frac{D_{w-m}}{D_{w-m} + 0.155 I_{cl} R T_s \beta} \quad (12)$$

The mean temperature of the skin is the function of the activity. A regression analysis of the data gave, for persons in thermal comfort, the following functional dependency between the skin temperature and activity level (internal heat production per unit surface area), [8]:

$$t_s = 35.7 - 0.032 \dot{q}_{Af} \quad (13)$$

Eqn (12) that describes the permeation efficiency factor for vapour transfer, enables to determine F_{pcl} as the function of: the total pressure p and velocity of gas v , composition of the breathing mixture x_i and total thermal resistance of the clothing I_{cl} . Evaporative heat loss from the clothed skin can be calculated as:

$$\dot{Q}_{ecl} = \beta_{cl} w r F_{pcl} (p_s - \varphi p_{sw}) \quad (14)$$

The fraction of the total surface that is wet (wettedness) is discussed in [9]:

$$w = 0.02 + 0.4 \{1 - \exp[-0.6(q_M / 58 - 1)]\} \quad (15)$$

Eqn (7), (12) and (14) enable to determine moisture gains and heat loss by evaporation of sweat inside the hyperbaric chamber.

4 The results of an experimental investigations

The permeation efficiency factor F_{pcl} for a certain clothing ensemble is rather difficult to measure in the hyperbaric environment. In order to obtain some experimental data in the hyperbaric environment, a series of experiments were undertaken to measure the coefficient of water evaporation defined by eqn (4) and the permeation factor F_{pcl} derived from eqn (12). Vapour diffusion resistance experiments were carried out for a given type of textile fibre. The experiments were performed in a 0.5m internal diameter, 0.183m³ hyperbaric chamber. The maximum working pressure was $p=5$ MPa, the working temperature was $t=0-50^\circ\text{C}$. Experiments were carried out in compressed air at the assumption that gas velocity $v = 0$. The laboratory hyperbaric set up is presented in [7,10]. Layers of the different cotton and artificial fibre were used to simulate clothing. The rate of water vapour diffusion from the evaporation dish was relatively easy to measure by observing the rate of weight change. The rate of mass transfer was obtained by measuring changes of weight in two cases: where evaporation dish was covered and uncovered with the layer of cloth. Experiments are reported in details in [7,10]. Based on experimental results for compressed air, the following formulas for the coefficient of water evaporation β and the permeation efficiency factor F_{pcl} were found.

- from the free surface:

$$\beta = 3.5999 \times 10^{-6} p^{-0.47} \quad (16)$$

-from the surface covered by cotton cloth (weight 101.51 g/cm^2):

$$\beta_{cl} = 25.7632 \times 10^{-6} p^{-0.7122} \quad (17)$$

-from the surface covered by artificial fibre cloth (weight 146.52 g/cm^2):

$$\beta_{cl} = 130.1967 \times 10^{-6} p^{-0.8606} \quad (18)$$

-for the cotton cloth (weight 101.51 g/cm^2):

$$F_{pcl} = 7.1566 \times 10^{-6} p^{-0.2422} \quad (19)$$

-for the artificial fibre cloth (weight 146.52 g/cm^2):

$$F_{pcl} = 36.1667 \times 10^{-6} p^{-0.3906} \quad (20)$$

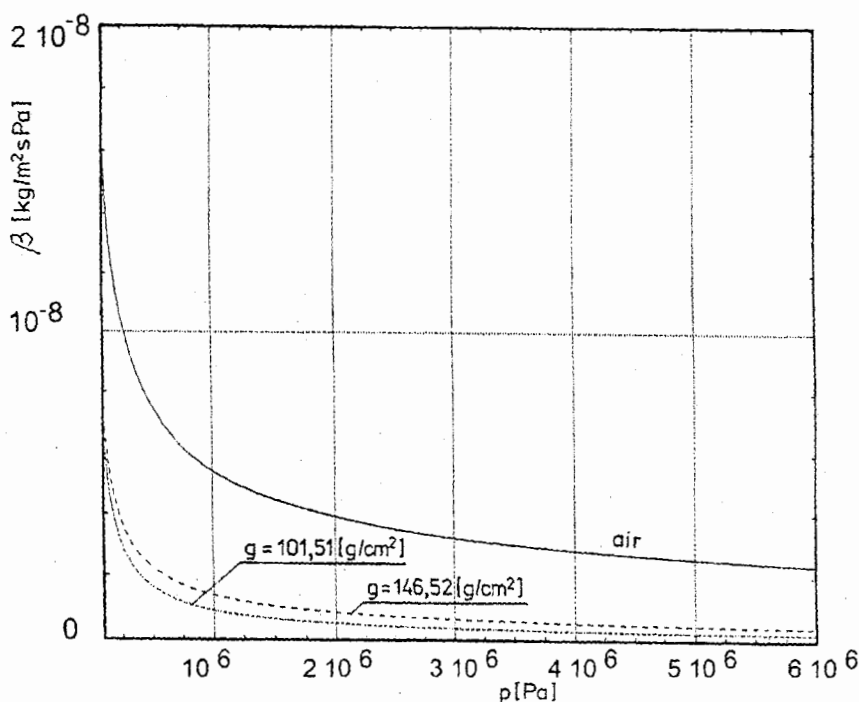


Figure 2: The relationship between the coefficient of water evaporation and the total pressure of air for three cases: without cloth, covered with cotton cloth (weight 101.51 g/cm^2), artificial cloth (weight 146.52 g/cm^2)

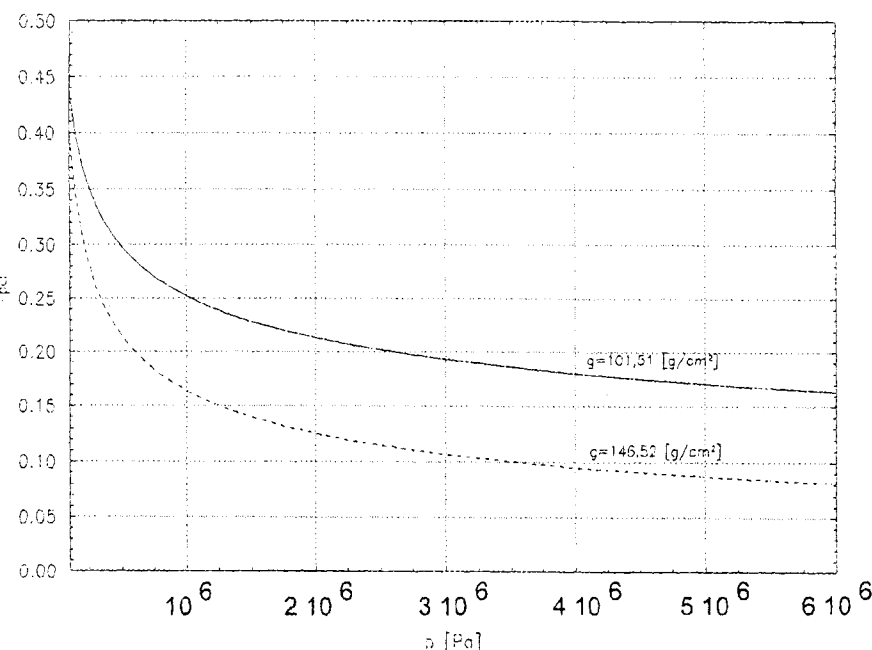


Figure 3: The relationship between the water vapour permeation factor and the total pressure of air for two cases: without cloth, covered with: cotton cloth (weight =101.51g/cm²), artificial cloth (weight =146.52g/cm²).

It is evident from Fig.2 and Fig.3 that in air atmosphere, the effect of the total pressure on the coefficient of water evaporation β and the permeation efficiency factor F_{pcl} is large, particular within the total pressure range $p=0.1-3$ MPa. The layer of cloth have also influence on decreasing of the coefficient of water evaporation β , however, the type of textile fibre does not seem to be of great significance in the hyperbaric environment.

Although the comparison between theory and the results of experiments carried out in air is relatively consistent [1,7,10] more research is needed, particularly for breathing mixtures containing helium.

6 Conclusions

- The permeation efficiency factor F_{pcl} has been defined, that describes the „cooling efficiency“ of sweating on the surface for a clothed human body in the hyperbaric chamber.
- The permeation efficiency factor F_{pcl} has been derived theoretically for the different kinds of the breathing mixtures as the function of: p - the total pressure, v -the relative gas velocity, I_{cl} - total thermal resistance the clothing. It may be

used as the first approximation to describe the process of sweat vaporisation through diver's normal clothing in the hyperbaric environment.

- Based on experiments in air atmosphere, the equations describing the relationship between the coefficient of water evaporation and the total pressure were derived. The coefficient of water evaporation decreases with the total pressure of gas.
- Based on experiments in air atmosphere, the equations describing the relationship between the permeation efficiency factor F_{pcl} and the total pressure were derived for the different clothes. The permeation efficiency factor F_{pcl} decreases with the total pressure of gas.
- The question now arises, how well evaporation of water from the free surface simulates the process of sweat evaporation from the diver's skin? The present paper concludes the first stage of research aimed with mass transfer in the hyperbaric environment.

NOMENCLATURE

A -the area, m^2 ,

A_{Du} -Du Bois area: body surface area of the human body, m^2 ,

D_{w-m} - mass diffusivity into the gas, m^2/s

F_{pcl} - the permeation efficiency factor for vapour transfer,

I_{dm} - the breathing gas layer resistance for water vapour, m^2sPa/kg ,

I_{dcl} - the cloth layer resistance for water vapour, m^2sPa/kg ,

I_m - heat transfer resistance of the breathing gas, m^2K/W ,

I_{cl} - total thermal resistance the clothing, clo, (1 clo = $0.155 m^2K/W$),

$\dot{m}_w$ - the water evaporation rate from the skin surface not covered by the clothing, kg/m^2s ,

$\dot{m}_{wcl}$ - the water evaporation rate from the skin surface covered by the clothing, kg/m^2s ,

p - the total pressure of gas, Pa,

p_s - saturated water vapour pressure at skin (surface) temperature, Pa,

p_{sg} - saturated water vapour pressure at ambient gas temperature, Pa,

$\dot{q}$ - heat flux transferred from the skin surface through the layer of gas mixture, W/m^2 .

$\dot{q}_{cl}$ - heat flux transferred from the skin surface through the layer of gas mixture and the cloth, W/m^2 ,

$\dot{q}_M$ - mean metabolic rate, W/m^2 ,

$\dot{Q}_e$ - evaporative heat flux from the naked skin, W,

$\dot{Q}_{ecl}$ - evaporative heat flux in the case of clothed body, W,

R -individual gas constant for water vapour, J/kg,

r - specific latent heat of vaporisation, J/kg,



t, T - gas temperature, °C, K
 t_s, T_s - temperature of the skin surface, °C, K.
 w - skin wettedness
 v - relative gas velocity, m/s,
 x_i - the molar fraction of i - component in the gas mixture,
 β - the coefficient of water evaporation in the hyperbaric environment,
kg/m²sPa,
 β_{w-m} - mass transfer coefficient of water, kg/m²s.
 δ - thickness of the gas layer, m,
 φ - the relative humidity of the gas.

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