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ISO 16976-5

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Respiratory protective devices — Human factors —

Part 5:
Thermal effects

Appareils de protection respiratoire — Facteurs humains —

Partie 5: Effets thermiques

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 94, *Personal safety — Personal protective equipment*, Subcommittee SC 15, *Respiratory protective devices*.

This first edition of ISO 16976-5 cancels and replaces the second edition (ISO/TS 16976-5:2020), which has been technically revised.

The main changes are as follows:

— requirements more specified.

A list of all parts in the ISO/TS 16976 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

For an appropriate design, selection and use of respiratory protective devices, basic physiological demands of the user should be considered. The function of a respiratory protective device, the way it is designed and used and the properties of its material can have a thermal effect on the human body.

This document belongs to a series of documents providing basic physiological and anthropometric data on humans. It contains information about thermal effects associated with wearing respiratory protective devices.

Respiratory protective devices — Human factors —

Part 5:
Thermal effects

1 Scope

This document is one part of a series of International Standards that provide information on factors related to human anthropometry, physiology, ergonomics and performance for the preparation of standards for design, testing and use of respiratory protective devices. This document contains information related to thermal effects of respiratory protective devices on the human body. In particular information is given for:

— temperatures of surfaces associated with discomfort sensation and harmful effects on human tissues;

— thermal effects of breathing gas temperatures on lung airways and tissues;

— effects of breathing gas temperature and humidity on respiratory heat exchange;

— effects of respiratory protective devices on overall body heat exchange.

The information represents data for adult healthy men and women in the age 20 years to 60 years.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 11079, *Ergonomics of the thermal environment — Determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects*

ISO 13732-1, *Ergonomics of the thermal environment — Methods for the assessment of human responses to contact with surfaces — Part 1: Hot surfaces*

ISO 13732-3, *Ergonomics of the thermal environment — Methods for the assessment of human responses to contact with surfaces — Part 3: Cold surfaces*

ISO 16972, *Respiratory protective devices — Vocabulary and graphical symbols*

3 Terms, definitions and abbreviations

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 16972 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1.1
clo
unit for the expression of the thermal insulation of clothing

Note 1 to entry: 1 clo is equal to 0,155 K m^2/W.

3.1.2
insulation required
IREQ
required clothing insulation for the preservation of body heat balance at defined levels of physiological strain

[SOURCE: ISO 11079:2007, 3.1.1]

Note 1 to entry: As determined according to ISO 11079.

3.1.3
predicted heat strain
PHS
analytical determination and interpretation of the thermal stress (in terms of water loss and rectal temperature) experienced by an average person in hot environments

Note 1 to entry: As determined according to ISO 7933.

3.2 Abbreviated terms and symbols

IREQ	Insulation required
PHS	Predicted heat strain
PPE	Personal protective equipment
PMV	Predicted mean vote
PPD	Predicted percentage dissatisfied
RPD	Respiratory protective device
SCBA	Self-contained breathing apparatus
T_s	Surface temperature (temperature of the surface contacted by skin)
T_a	Ambient temperature (temperature of the air surrounding the body or inhaled)
T_c	Contact temperature (temperature of the interface between skin and contacted surface)

4 Local thermal effects

4.1 General

The effects of heat and cold described in this document will vary according to individual sensitivity.

Notice should be taken of the assessment scales given in ISO 8996.

4.2 Effects on skin contact by the RPD

Heat transfer by conduction takes place via the hands when handling the equipment and via face, head and torso during the actual use of the equipment.

Parts of RPD are, by their very nature, in more or less direct contact with naked human skin, e.g. the face. In contact areas heat exchange will be affected. The magnitude of this effect is dependent on contact pressure, structure of surfaces, size of contact area, mass of material in contact, thermal conditions and thermal properties of materials in contact.

Materials used in RPD are mostly made of materials with low conductive heat transfer properties. Exceptions are metal parts, in particular, if they are not insulated.

In extreme hot or cold environments, the ambient conditions can heat or cool the RPD or parts of it, thereby increasing the risk of a thermal effect on the skin.

A risk assessment of contact cooling or heating of the bare skin shall be based on

— ISO 13732-1, for hot surfaces, and

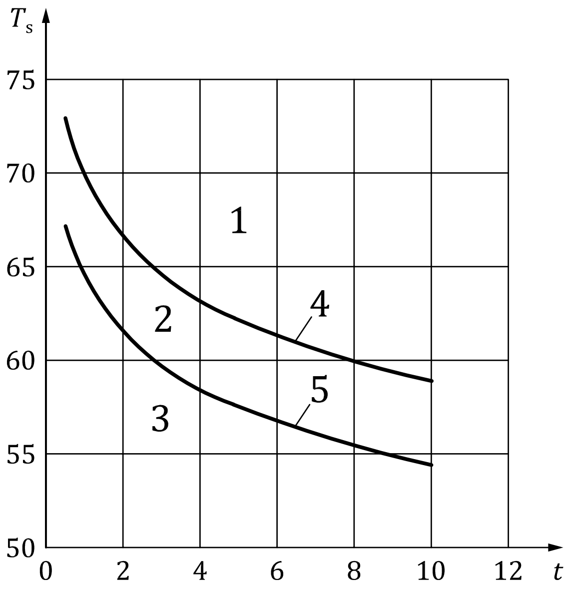
— ISO 13732-3, for cold surfaces.

Exposure values and criteria used in the figures below are based on hand or body skin surface contacts. Face skin is likely to be more sensitive in particular to discomfort and more conservative values should be used.

4.3 Hot surfaces

ISO 13732-1 provides comprehensive information about the risk of bare skin contacting different types of materials at different temperatures. Figure 1 shows surface temperatures of polished aluminium metal that can cause skin burns. This condition appears to be the most severe case, but other metals such as steel and copper can be as harmful at similar or slightly higher temperatures. Other materials like plastic, glass and ceramics require considerably higher temperature to cause harm to bare skin.

For these materials the zone 3 “safe surface” in Figure 1 moves up to the line 4, i.e. upper limit.



Key

t time, in s

T_s surface temperature, in °C

1 zone 1 indicates a high risk of skin burn

2 zone 2 indicates a possible risk of skin burn

3 zone 3 indicates safe surface temperatures

4 upper limit

5 lower limit

Figure 1 — Surface temperature of polished aluminium metal that can cause skin burns

RPD is likely to be used for short duration timed in minutes and longer duration timed in hours. Table 1 indicates burn thresholds for contact periods of 1 min and longer for different materials (modified from ISO 13732-1). Values apply for contact areas that are less than 10 % of the body surface, so they should apply for most RPD.

Table 1 — Burn threshold for contact periods of 1 min and longer

<table>
<tr><th rowspan="2">Material</th><th>1 min</th><th>10 min</th><th>8 h and longer</th></tr>
<tr><th colspan="3">°C</th></tr>
<tr><td>Uncoated metal</td><td>51</td><td rowspan="5">48</td><td rowspan="5">43</td></tr>
<tr><td>Coated metal</td><td>51</td></tr>
<tr><td>Ceramics, glass and stone materials</td><td>56</td></tr>
<tr><td>Plastics</td><td>60</td></tr>
<tr><td>Wood</td><td>60</td></tr>
</table>

4.4 Cold surfaces

ISO 13732-3 provides detailed information about the assessment of cooling effects on skin in contact with various types of cold surfaces. Information is given about five types of materials: aluminium, steel, stone, plastic and wood. For each of the materials three criteria for cooling are applied.

As with a hot surface contact with a small skin surface area with cold, metallic goods can rapidly cool the skin and eventually result in local frostbite. Figure 2 and 3 show cooling curves obtained with the fingertip touching surfaces of steel and aluminium at temperature of −20 °C, −30 °C and −40 °C. The contact temperature, T_c, which is likely to be very close to the skin surface temperature drops to below

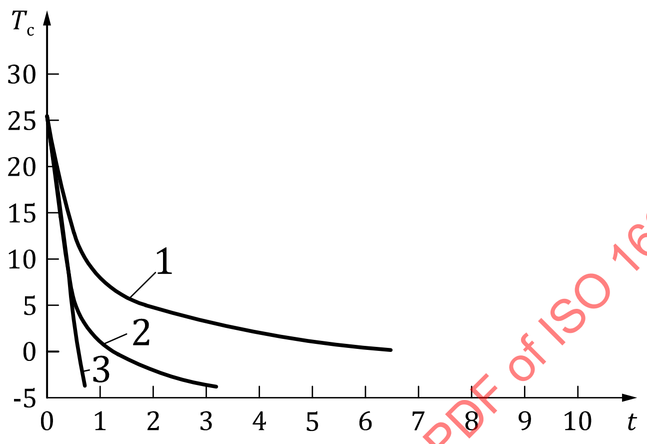
0 °C within few seconds when touching the metallic surfaces (see Figure 2 and 3). The risk of developing local frostbite is highly probable.

Studies[6] have shown that:

— Cooling to a skin temperature of 0 °C is associated with an imminent risk of tissue freezing “frostbite”.

— Cooling to a skin temperature of +7 °C is associated with the gradual development of numbness.

— Cooling to a skin temperature of +15 °C is associated with the experience of pain.



Key

t time, in s

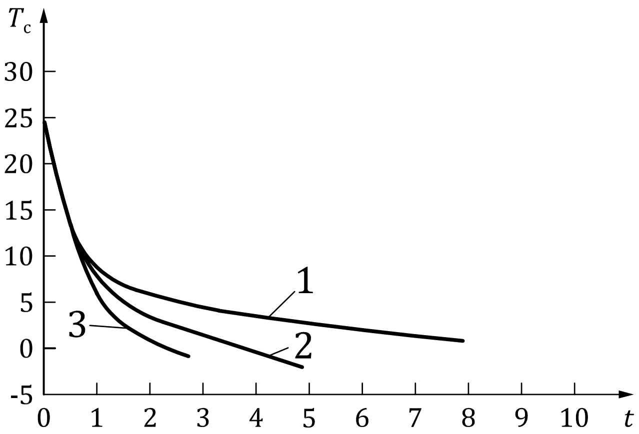
T_c contact temperature, in °C

1 −20 °C

2 −30 °C

3 −40 °C

Figure 2 — Change in T_c of finger in contact with steel surfaces at temperatures of −20 °C, −30 °C and −40 °C



Key

t time, in s

T_c contact temperature, in °C

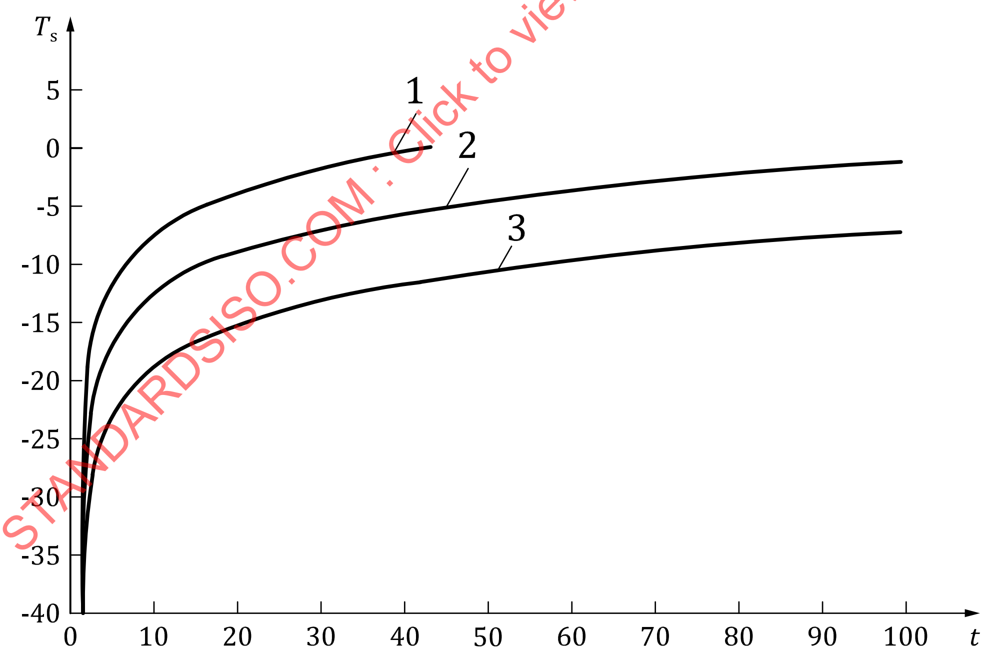
1 −20 °C

2 −30 °C

3 −40 °C

Figure 3 — Change in T_c of finger in contact with aluminium surfaces at temperatures of −20 °C, −30 °C and −40 °C

Figure 4 to Figure 6 show the surface temperature of a specific material that might cause the different type of cooling effects[6].



EXAMPLE The information given in Figure 4 shows that when holding a piece of aluminium (key 1) at 0 °C frostbite would result after about 45 s, whilst holding a piece of stone (key 3) at −10 °C frostbite would result in about 70 s.

Key

t contact duration, in s

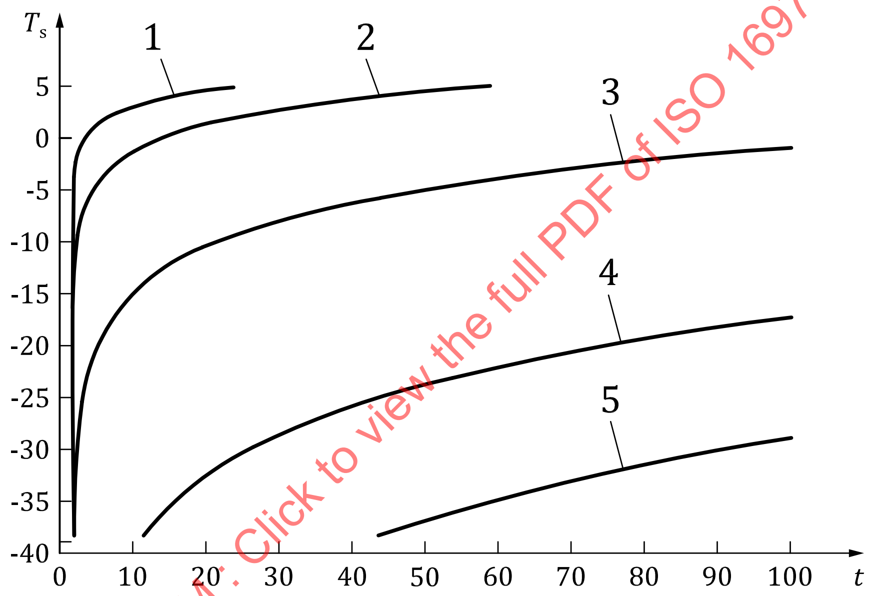
T_s surface temperature, in °C

1 aluminium

2 steel

3 stone

Figure 4 — Frostbite threshold: acceptable surface temperature as a function of time for T_c to reach 0 °C (finger touching the cold surfaces between 0,5 s and 100 s)



EXAMPLE The information given in Figure 5 shows that when holding a piece of wood (key 5) at −30 °C numbness would result after about 90 s, whilst holding a piece of steel (key 2) at −5 °C numbness would result in about 5 s.

Key

t contact duration, in s

T_s surface temperature, in °C

1 aluminium

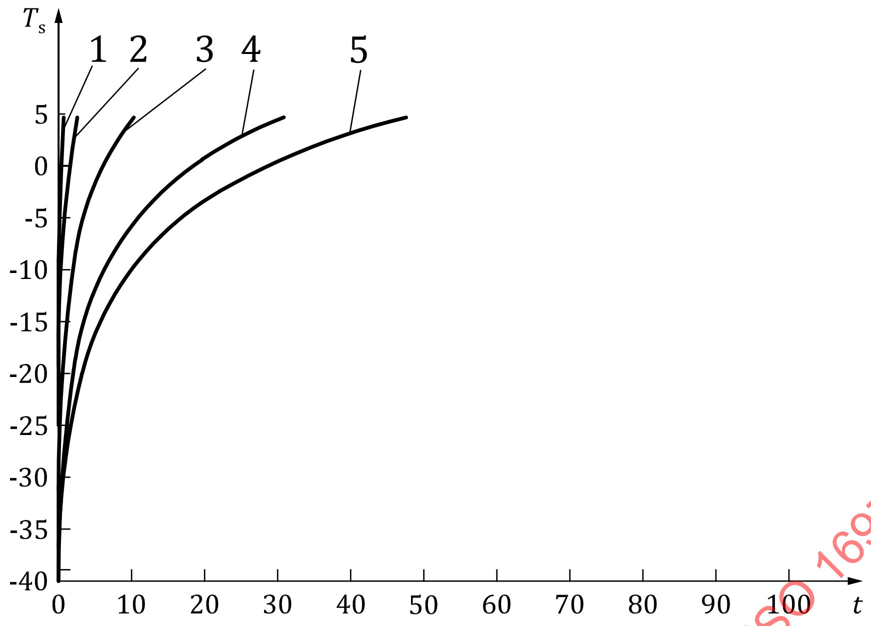
2 steel

3 stone

4 nylon

5 wood

Figure 5 — Numbness threshold: acceptable surface temperature as a function of time for T_c to reach 7 °C (finger touching the cold surfaces between 0,5 s and 100 s)



Key

t contact duration, in s

T_s surface temperature, in °C

1 aluminium

2 steel

3 stone

4 nylon

5 wood

Figure 6 — Pain threshold: acceptable surface temperature as a function of time for T_c to reach 15 °C (finger touching the cold surfaces between 0,5 s and 100 s)

4.5 Effects of inhaled breathable gas to, airways and lung tissues

4.5.1 General mask function

During respiration there is a heat exchange function also for the RPD. There is at least initially a cooling effect on hot air and a warming effect of cold air. This effect is not well known and depends on type of respirator, material, activity level and environmental conditions. For example, the use of high pressure compressed air should present no problem in hot air as air is cooled during the expansion from the tube. In contrast RPD whose function is based on chemical reaction can present a problem as the breathable gas is heated by the chemical process.

Inhaled breathable gas has low density and low heat capacity. The anatomical and physiological construction of the airways, in particular the upper respiratory tract, provides significant features for preservation of body heat and moisture and mitigation of environmental cooling or heating.

4.5.2 Effects caused by hot breathable gas

At very high temperatures inhaled breathable gas can result in pain sensation and eventually in tissue burn. During short exposures nasal breathing becomes difficult at 125 °C ambient, dry inhaled breathable gas temperature. Mouth breathing becomes difficult at 150 °C ambient, dry inhaled breathable gas temperature. Moist inhaled breathable gas will increase heat exchange and significantly shorten tolerance time at high temperatures. Water saturated inhaled breathable gas at 60 °C to 70 °C increases discomfort at rest (steam sauna) and will be intolerable for longer times during activity.

With RPD tolerable temperatures are likely to be much lower due to longer exposure times and higher ventilation rates. Warm or hot inhaled breathable gas will also heat the respiratory interface, contributing to a local conductive heat gain in the face/head area.

It is known that at high inhalation temperatures and relative humidity irritation of the lung tissues and air ways can occur. For example, at temperature levels of 100 °C at less than 20 % RH at “light work” or 70 °C at less than 70 % RH at “moderate work” or even 40 °C with up to 100 % RH at “very high work” might cause irritation, see Table 2.

Table 2 — High temperature that refer to sensorial effects

<table>
<tr><th rowspan="2">Class</th><th rowspan="2">Work</th><th>Average metabolic rate</th><th colspan="3">Relative humidity level</th></tr>
<tr><th>W/m²</th><th>≤20 %</th><th>≤70 %</th><th>≤100 %</th></tr>
<tr><td>1</td><td>Resting</td><td>65</td><td rowspan="3">90</td><td rowspan="3">70</td><td rowspan="3">50</td></tr>
<tr><td>2</td><td>Light work</td><td>100</td></tr>
<tr><td>3</td><td>Moderate work</td><td>165</td></tr>
<tr><td>4</td><td>Heavy work</td><td>230</td><td rowspan="5">80</td><td rowspan="5">65</td><td rowspan="5">45</td></tr>
<tr><td>5</td><td>Very heavy work</td><td>290</td></tr>
<tr><td>6</td><td>Very, very heavy work (2 h)</td><td>400</td></tr>
<tr><td>7</td><td>Extremely heavy work (15 min)</td><td>475</td></tr>
<tr><td>8</td><td>Maximal work (5 min)</td><td>600</td></tr>
</table>

4.5.3 Effect caused by cold breathable gas

At very low temperatures inhaled breathable gas cools the airways, eventually resulting in broncho-constriction and epithelial irritation. Symptoms can be coughing and asthmatic like reactions.

ISO 11079 suggests the following temperature limit values for, cold inhaled breathable gas. The low strain values refer to effects of more sensorial type, such as discomfort. The high strain level indicates values that can cause irritation, coughing and eventually long-term health effects such as asthmatic symptoms.

Breathable gas through a RPD at such low temperatures is not very likely to cause harm as the respiratory interface itself will act as a kind of heat exchanger and provide some re-warming of inhaled breathable gas.

It is known that at low inhalation temperatures and relative humidity irritation of the lung tissues and air ways can occur, see Table 3.

EXAMPLE At inhalation temperature level of −40 °C at “light work” or −30 °C at “moderate work” or −20 °C at “very high work” irritation can occur.

Table 3 — Low inhalation temperature that refer to sensorial effects

<table>
<tr><th>Class</th><th>Work</th><th>Average metabolic rate
W/m²</th><th>Inhalation temperature at relative humidity level ≤20 %
°C</th></tr>
<tr><td>1</td><td>Resting</td><td>65</td><td rowspan="2">−40</td></tr>
<tr><td>2</td><td>Light work</td><td>100</td></tr>
<tr><td>3</td><td>Moderate work</td><td>165</td><td>−30</td></tr>
<tr><td colspan="4">NOTE The time limits for Classes 6 to 8 are due to peoples’ limited physical work abilities at these high levels (see ISO 16976-1).</td></tr>
</table>

Table 3 *(continued)*

Class	Work	Average metabolic rate W/m^2	Inhalation temperature at relative humidity level ≤20 % °C
4	Heavy work	230	−20
5	Very heavy work	290	
6	Very, very heavy work (2 h)	400	−30
7	Extremely heavy work (15 min)	475	
8	Maximal work (5 min)	600	−40
NOTE The time limits for Classes 6 to 8 are due to peoples' limited physical work abilities at these high levels (see ISO 16976-1).			

5 Effects on whole body heat balance

The body exchanges heat with the environment basically through the respiratory system and via the skin. Heat exchange by respiration comprises convective and evaporative components.

5.1 Respiratory heat exchange

Respiratory heat loss accounts for 5 % to 15 % of the body's heat loss depending on the level of activity. Heat transfer to hot and cold air through the airways is controlled to some extent, in particular with nasal breathing. With moderate to heavy exercise mouth breathing is necessary and the heat and moisture exchange becomes less efficient. In the cold it adds to respiratory heat loss and in the heat it reduces respiratory heat loss. On the other hand the breathing mask, a filter and the dead space can provide some damping of the immediate effect of environmental temperatures. In high heat and high humidity situations the mask worn can exacerbate the effect. The magnitude of these effects is not known.

Respiratory heat exchange can be described as a function of the minute ventilation and the temperature difference between inhaled and exhaled air.

The following empirical Formulae (1) to (3) have been proposed:

$$E_{res} = 0{,}017\,3M(p_{ex} - p_a) \qquad (1)$$

$$C_{res} = 0{,}001\,4M(t_{ex} - t_a) \qquad (2)$$

$$t_{ex} = 29 + 0{,}2t_a \qquad (3)$$

where

E_{res} is the evaporative heat exchange, in W/m^2;

C_{res} is the convective respiratory heat exchange, in W/m^2;

M is metabolic rate in W/m^2;

p_{ex} is the water vapour pressure of expired air, in kPa;

p_a is ambient water vapour pressure, in kPa.

It is assumed that expired air is water saturated and has a temperature, t_{ex}, that is related to inspired (ambient) temperature, t_a, by Formula (3).

Convective heat exchange is normally quite small but can reach noticeable magnitudes in certain circumstances. Evaporative respiratory heat loss is generally greater than the convective component RPD using compressed as a source can provide cool and dry air that can be beneficial in hot environments but a disadvantage in cold conditions.

Under conditions when RPD can cause increased levels of inhaled CO_2, ventilation can increase, enhancing respiratory heat loss (see ISO 16976-3).

In hyperbaric environments respiratory heat exchanges increase in proportion to the increased ambient pressure. In deep sea diving heating of air can be required in order to compensate for respiratory heat losses. This is particularly true if helium is used as a breathing gas to a larger extent.

RPD using compressed air as a source provides dry air that in most cases is inhaled at a lower temperature than ambient due to decompression. This means that more evaporative heat and more water is lost for the same minute ventilation than under normal breathing conditions. This provide for some extra heat loss in warm environments but at the expense of increased water loss.

In the cold the extra heat loss can still be positive at high work rates. At lower work rates the extra heat loss can require compensation by e.g., extra clothing for the maintenance of heat balance. At high work rates in the heat associated with mouth breathing, more heat is expelled to the environment and therefore is a positive effect.

5.2 Skin surface heat exchange

Most of the body heat dissipates via the skin. The impact of a RPD is thus much dependent on the coverage of the skin surfaces and the properties of the material that covers the skin.

The head is important for heat exchange both from a subjective and physical point of view. The head is more sensitive to thermal stimuli than many other parts of the body. The head and neck represent approximately 10 % of the body surface area. It is a significant area for heat exchange, particularly in the cold. Blood flow to head and brain is not reduced in the same manner as to extremities during vasoconstriction. Certain types of RPD can have even large of coverage of the body. For ventilated chemical protective suits it can be 100 %.

Thermal effects of respiratory interfaces are likely to be more of a sensorial nature – comfort/discomfort. The quantitative effect of a mask on whole body heat exchange is small. In the heat it is likely to add to thermal discomfort. In the cold the mask provides an additional protection of the face area due to its insulation and the heat exchange effect. Contact with cold metal parts shall be avoided.

RPD with a hood implies coverage of the head and parts of the upper torso with material that is impermeable to water vapour. Evaporative heat exchange of covered areas is affected. On the other hand, hood systems usually have assisted ventilation. This can improve or impair the thermal conditions depending on the outside environment. In a cold environment ventilation can increase local heat losses and contribute to a larger overall body heat loss. In a warm environment, ventilation improves local evaporation and slightly reduces heat stress. Only in very hot and humid conditions is a negative effect expected.

In some user applications the RPD is combined with other types of personal protection. In these conditions the thermal effects can be large, for example with a chemical protective suit or a fire fighter turnout gear. Exposure times often become limited to 30 min to 60 min due to the availability of breathable gas as well as due to rising levels of heat stress. Technical solutions are available that provide means of cooling the clothing microclimate, for example by supplying air for ventilation or by using phase change materials (PCM) in suits or extra vests. The heat exchange in these conditions can be analysed and the contribution of RPD and other personal protection can be calculated.

5.3 Increased metabolic rate

Through assessment of respiratory and skin heat fluxes it is possible to make an analysis of the conditions for whole body heat exchange. This is necessary for an estimation of possible risks of hyperthermia or hypothermia.

