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Sodobni izolacijski materiali in evakuirane ploščate strukture**Modern Insulating Materials and Flat Evacuated Structures**

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V prispevku so podane omejitve lastnosti današnjih materialov in možnosti izdelave okolju prijetnejših in učinkovitejših vakuumskih elementov in struktur. Predstavljene so naše raziskave tankih evakuiranih struktur, za nadaljnje izboljšanje izolirnosti.

In this paper, limitations of the insulating value of today widely used materials and possible alternatives for "green" and more efficient vacuum insulating structures are given. Our results on research of more efficient thin insulating panels, are also given.

0 UVOD**Pregled izolacijskih materialov****0 INTRODUCTION****Review of insulating of materials**

V termično izolacijskih materialih je izolirnost dosežena na račun zmanjšane prevodnosti v trdni snovi zaradi nizke gostote ter mnogih zožitev in podaljšanja prevodnih poti, prevajanja ujetega plina (brez konvekcije) in oteženega razširjanja toplotnega sevanja zaradi sisanja. Spodnja meja skupne toplotne prevodnosti za izolacijske vlaknate materiale pri sobni temperaturi, ko je v strukturi zrak pri atmosferskem tlaku, je okoli 0.04 W/m K . Po grobi delitvi je petina te vrednosti prevajanje po trdni snovi ($\lambda_{\text{steklo}} = 1 \text{ W/m K}$) in termično sevanje, pretežni del je torej prestopanje zraka ($M = 29$, $\lambda_{\text{zrak}} = 0.026 \text{ W/m K}$). Pri gostoti steklene volne od 150 do 200 kg/m^3 je dosežena meja zadovoljive mehanske trdnosti za izdelavo poltrdih plošč. Pri še manjših gostotah, pri katerih je danes moč izdelovati vlaknate mehke materiale, $\rho = 40 \text{ kg/m}^3$, lahko nastajajo konvekcijski tokovi, kar ponovno zmanjšuje izolirnost. Zaradi zmanjšanja gostote se slabšajo tudi mehanske lastnosti, kar povzroči pri navpični uporabi sesedanje, lezenje in trganje. Za preprečitev teh pojavov so potrebne dodatne opore ali močnejši okrov [14]. Izolacijski materiali te skupine so občutljivi na kopičenje vlage na hladnih mestih, kar zmanjšuje izolirnost in lahko povzroča poškodbe nosilne konstrukcije. Zaradi tega morajo biti vgrajeni s parno zaporo. Glede primernosti za okolje so vlaknati materiali nestrupeni, že dolgo pa so v skupini dokazanih povzročiteljev alergij in poškodb dihal.

In thermal insulating materials, insulating properties are related to low density since the solid conductivity is minimized due to prolonged and constricted heat paths, low conductivity of residual gas (without convection) and scattering of thermal radiation. Overall heat conductivity of fiber materials (mineral and glass wool) is due to the aforesaid mechanisms, at room temperature and atmospheric pressure, limited to approx. 0.04 W/m K . By rough division, one fifth of this value is due to solid conductivity ($\lambda_{\text{glass}} = 1 \text{ W/m K}$), another fifth due to radiation, while a major part is due to gaseous conductivity of the air, ($M = 29$, $\lambda_{\text{air}} = 0.026 \text{ W/m K}$). At the density of 150 to 200 kg/m^3 , mechanical properties allow us to press boards of glass wool which are stiff enough to be handled easily. Further decrease of density down to $\rho = 40 \text{ kg/m}^3$, at which today wools can be fabricated, cause greater convection losses, which decrease overall insulating value. Low density wools have worse mechanical properties, which cause, when they are used vertically, sedimentations creeping and tearing. To prevent such phenomena, further mechanical supports and stronger housing are needed [14]. This group of materials is also sensitive to water condensing in colder parts of buildings, which lessen thermal properties but can also cause corrosion of construction. These can be prevented by the use of water impermeable foil. Regarding their environmental acceptance, these materials are not toxic, but belong to the group of substances which influence allergies and lung diseases.

Podobne izolacijske lastnosti kakor steklena in mineralna volna, vendar s precej nižjo dovoljeno temperaturo uporabe, ima ekspandirani polistiren (stiropor), danes nepogrešljiv v gradbeništvu. Ker je neprepusten za vodo, ne potrebuje nujno parne zapore, žal pa je gorljiv. Prištevamo ga med ekološko sprejemljive materiale, ker je z leti razgradljiv po naravni poti.

Poliuretantske (PU) pene so pomenile v času uvajanja, v sredi sedemdesetih, skoraj revolucijo pri izdelovanju hladilnikov in drugih naprav. Med kemijsko reakcijo ekspandirajo v pripravljen model ali že med fiksirani steni, procesni plin z veliko molekulsko maso pa ostane ujet v strukturi. Termična prevodnost poliuretana je $0,25 \text{ W/m K}$. V penasti strukturi z gostoto $\rho = 30 \text{ kg/m}^3$ pomeni prevajanje po trdni snovi le $\lambda = 0,006 \text{ W/m K}$. Žal pa togost plošč za mnoge primere uporabe ni več zadovoljiva. Zmanjšanje deleža plinskega prestopanja, ko je v strukturi pretežno plin z veliko molekulsko maso, npr. CFC-11 oziroma freon R-11 (triklorofluorometan, $M \approx 137$, $\lambda = 0,008 \text{ W/m K}$), omogoči zmanjšanje skupne topotne prevodnosti celo pod $\lambda = 0,02 \text{ W/mK}$. Ob nedvomni izjemni izolirnosti je treba dodati pomanjkljivosti, od katerih je bila ena opažena deset let prepozno.

- Sproščanje ujetih, ozonski plasti škodljivih kloriranih in fluoriranih spojin med uporabo (in na odlagališčih). Ob tej zamenjavi z zrakom, ki poteka z difuzijo, se zvečuje prevodnost, [5].

- Hidrofilnost kot pogost vzrok nepopravljivih napak hladilnih naprav na slabo tesnjenih mestih ovojnice.

Zamenjave agresivnega R-11 z manj nevarnimi plini se kažejo v spremenjenih lastnostih pen. Upoštevati je treba spremenjeno prevodnost, topnost in interakcijo s polimerom, difuzijo in permeacijo, strupenost, gorljivost, ceno itn. CO_2 ($M = 44$, $\lambda = 0,016 \text{ W/m K}$) zniža izolirnost in se z difuzijo bistveno prej izgubi iz ovojnice kakor težji plini. Pentan (navadni ali ciklirani, $M = 72$, $\lambda = 0,014 \text{ W/m K}$) ali drugi gorljivi ogljikovodiki postopek izdelave nekoliko podražijo zaradi nevarnosti eksplozije. (V 1 m^3 izolacije je nekaj kilogramov pentana). Ogljikovodiki so dandanes edina zelena zamenjava, vpeljana v industrijskem merilu, (Gorenje v 1994). Priprava pen z žlahtnima plinoma, kriptonom ($M = 84$, $\lambda = 0,013 \text{ W/m K}$) ali ksenonom ($M = 131$, $\lambda = 0,008 \text{ W/m K}$), bo že zaradi cene žlahtnih plinov in neprilagojenih postopkov penjenja za široko uporabo predraga.

Similar insulating properties as glass or mineral wool, but with substantially lower maximum allowed temperature of use, are exhibited by expanded polystyrene (Styropor), today widely used in buildings. Since it is hydrophobic, it can be built in without impermeable foil, but unfortunately it is flammable. It belongs to the group of ecologically acceptable materials since it can be degraded in prolonged time on natural way.

Polyurethane (PU) foams, which started to be used on industrial scale in the mid seventies, caused a revolution in technology of producing refrigerator housings. During a controlled chemical reaction, the quantity of foam is expanded in preset volume between fixed walls while an expanding gas of a high molecular mass rests in the structure. Thermal conductivity of solid polyurethane is $\lambda = 0.25 \text{ W/m K}$, but in foam with a density of $\rho = 30 \text{ kg/m}^3$, the solid component of conductivity is only $\lambda = 0.006 \text{ W/m K}$. Boards, made of so porous foam, are not rigid enough for all types of application. Reduction of gaseous conductivity when a gas with high molecular mass for example CFC-11 (tri-chloro-fluoro-methane, $M \approx 137$, $\lambda = 0.008 \text{ W/m K}$), is present in the foam, lead to an overall thermal conductivity below $\lambda = 0.02 \text{ W/mK}$. Among its undoubtedly extraordinary insulating properties, disadvantages must be mentioned, too. One of them was recognized ten years too late.

- Releasing of gaseous compounds of CFC group with different aggression to ozone, (CFC11 the most widely used being the worst) during use and after it. Air, which replaces the CFCs in the foam, increases it's conductivity.

- Hydrophilic nature of foams causes several damages of refrigerating units, specially at non tight corners of the housings.

Replacement of CFC11 with other gases manifests itself in different foam properties. Different gases dissolve in polymer differently, with changed constants of diffusion and permeation; they should not be flammable, toxic and must be available at a reasonable price etc. Carbon dioxide, CO_2 ($M = 44$, $\lambda = 0.016 \text{ W/m K}$), as the promising candidate, reduces insulation value and diffuses out of the foam much easier than heavier gases. Pentane (normal or cyclo-, $M = 72$, $\lambda = 0.014 \text{ W/m K}$) and other hydrocarbons slightly increase manufacturing price due to explosion hazard. (In 1m^3 of the foam, there are some kg of the gas). Anyhow, hydrocarbons, even though they offer lower insulating value than CFCs, are today the only green replacement for CFC compounds, introduced on industrial scale, (Gorenje in 1994). Expanding foams with noble gases, like krypton ($M = 84$, $\lambda = 0.013 \text{ W/m K}$) or xenon, ($M = 131$, $\lambda = 0.008 \text{ W/m K}$), will remain just an option, hardly realized in practice due to their higher price and non compatible foaming procedure.

Bistveno znižanje prevodnosti pri atmosferskem tlaku katerega koli plina v omenjenih strukturah torej ni mogoče.

1 EVAKUIRANE STRUKTURE

Zniževanje tlaka v makroskopsko razčlenjenih materialih, ki se zdi preprosta rešitev za skupno zmanjšanje prevodnosti, prinese precej sprememb:

- material mora biti ločen z ovojnico,
- zahtevano poroznost je treba ohraniti tudi pri delovanju atmosferskega tlaka, ki lahko precej poveča povprečno gostoto in prevajanje v trdni snovi,
- prevajanje plina se ne zmanjša dokler tlaka ne znižamo za nekaj razredov velikosti,
- dolgotrajna uporaba evakuirane strukture postavlja dokaj resne zahteve za tesnost in trdnost ovojnice, ki mora biti dosežena ob njenem najmanjšem prečnem prevajanju.

Učinek skupnega zmanjšanja prevodnosti v materialu, do katerih pride pri zniževanju tlaka, je mogoče uporabiti torej le skupaj s prispevkom, ki ga prinese ovojnica, kar delno zasenči njihovo privlačnost. Namesto izraza termični izolacijski "materiali" bi bil tako primernejši izraz evakuirane izolacijske strukture.

Nedvomno so evakuirane strukture po tej definiciji tudi devarske (J.Dewar jih je izumil ob koncu 19. stoletja) posode oziroma termovke. Te učinkovito izrabljajo izolirnost reže pri močno razredčenem plinu in majhno oddajanje posrebrenih sten, steklene stene pa so razmeroma debele. Izboljšane devarske kovinske posode z nekaj plastmi reflektorjev, (t.i. superizolacija SI), prav tako nameščenih v reži in visokem vakuumu so daleč najbolj izolirne strukture, kar jih znamo pripraviti. Navidezna prevodnost za neobremenjeno SI je pod $\lambda = 10^{-4}$ W/m K. Posode imajo to pomanjkljivost, da so zaradi nujno potrebnih nosilnih sten težke in da jih je treba po nekaj letih ponovno izčrpati. Omejene so na obliko valja ali krogla. Zaradi cene in težav pri doseganjу stabilnega vakuma so superizolirane posode načrtovane predvsem za zelo nizke (krio)temperature.

Kljub zgodnjemu odkritju in dokazanim izolativnim lastnostim posod z evakuirano režo, (ali mikroporoznih nasutij, omenjenih kasneje), so se resne razprave o možnostih izdelave ploščatih devarskeih panelov pojatile kasneje, [13]. Stanje razvoja je desetletja ostalo na stopnji laboratorijskih vzorcev, ki so omogočila nastanek znanstvenih poročil in patentov [2]. Objave o končanem razvoju, pripravi oz. začetku pilotne proizvodnje plošč z mikroporoznim nasutjem pa zasledimo v devetdesetih letih [12].

Any substantial decrease of conductivity in mentioned structures with any kind of applied gas at the atmospheric pressure is not possible.

1 EVACUATED STRUCTURES

Reducing of residual pressure in those macroscopically porous materials, which seems an easy solution for overall reduction of conductivity, brings several changes:

- material must be kept in a tight envelope,
- required porosity must be preserved when loaded with atmospheric pressure, which influences density and solid conductivity
- gaseous conductance does not drop until pressure is reduced by several orders of magnitude
- long term usefulness of evacuated structure sets high requirements for tightness and mechanical stiffness of the envelope which must be realized at its minimum lateral conduction.

Lower conductivity which would result at reduced pressure can be used together with a contribution from the envelope's is lateral conductivity, which makes this possibility less attractive. The use of the term "thermal insulating material" should be replaced by "evacuated structure".

By this definition of evacuated structures, Dewar flasks or (Thermos) bottles also belong to this group. They were invented by Sir J.Dewar at the end of 19.cent. The low gas conductivity and low emissivity of silvered internal surfaces are employed in a very efficient way even if the glass walls are relatively thick. Improved performances of such vessels can be realized by introducing several metal reflectors, mounted in the gap perpendicular to heat flow. Such vessels, named also "superinsulated" (=SI) Dewars, have by far the lowest thermal conductivity, known today. Apparent conductivity, always given a non loaded SI structure, is even below $\lambda = 10^{-4}$ W/m K. These types of vessels have the same disadvantages, they are heavy and need to be repumped after some period. Their shape is limited to cylinder or sphere. Due to high price manifesting difficulties in obtaining a stable vacuum, they are mostly designed for use at cryo temperatures.

Even if the effect of reduced conductivity in evacuated structures employing a gap (or microporous powder, discussed later) was known for decades, there were few serious discussions about flat Dewar panels, [13]. The state of development rested at the level of laboratory samples, which enabled the writing of scientific reports or patents, [2]. Reports about the final stage of developments, which led to pilot plant production of microporous powder filled panels, are dated from the nineties, [12].

2 KRATEK PREGLED DELEŽEV PRENOŠA TOPLOTE V EVAKUIRANIH STRUKTURAH

2.1 Prevajanje v trdni snovi

Prevajanje toplote je po analogiji z električnim tokom v kovinah še najlaže predstavljivo. Modeli prevajanja toplote v trdni strukturi, ki upoštevajo zožitve in dejansko podaljšanje prevodne poti, se tako za pene, kakor za praškasta nasutja in vlaknate snovi dobro ujemajo z meritvami. Žal se pene in volne pri obremenitvah, ki jih povzroči atmosferski tlak, zgostijo ali sesedejo, prevodnost pa se poveča. Večji del zmanjšanega prevajanja v trdni snovi v nasutjih lahko opišemo s preprostim modelom Hertzovih kontaktov med gladkima elastičnima kroglama (z različnimi polmeroma r , moduloma elastičnosti E , Poissonovima številoma μ). Pri delovanju sile F se vzpostavi stik na razmeroma majhni ploskvi, katere polmer, t.i. Hertzov polmer r_c , dobimo z enačbo:

$$r_c = \sqrt[3]{\frac{3F}{4} \cdot \left(\frac{1}{r_1} + \frac{1}{r_2} \right)^{-1} \cdot \left(\frac{1 - \mu_1^2}{E_1} + \frac{1 - \mu_2^2}{E_2} \right)} = \sqrt[3]{\frac{3FR}{4E^*}} \quad (1).$$

V desnem izrazu sta izraza v oklepajih, za ukrivljenost in elastičnost iz levega izraza, nadomeščena z dejansko vrednostjo, R in E^* .

Nastala zožitev pomeni za toplotni tok omejitev, kontaktni upor. Inverzno vrednost, prevod stika, izrazimo po izračunu iz osnov elektrotehnike kot zmnožek premora ploskve in prevodnosti materiala, iz katerega sta krogli:

$$k_c = 2r_c \cdot \lambda_{solid} \quad (2).$$

Na nasutje krogel v kubičnem sestavu naj deluje zunanjji tlak p . Na enoto dolžine lahko razporedimo mnogokratnik premora krogel, sila na kontakt pa je sorazmerna s ploskvijo, torej premerom na kvadrat. Za toplotno prevodnost nasutja krogel (lastni tlak smo zanemarili) sledi po enačbah (1) in (2) preprosta zveza:

$$\bar{\lambda}_{solid} = \lambda_{solid} \cdot \sqrt[3]{\frac{3p}{4E^*}} \quad (3).$$

Rezultat je zanimiv, ker v izrazu ni odvisnosti od premera krogel. Za steklo z najnižjo vrednostjo med primernimi materiali in $E^* = 7 \cdot 10^{10}$ Pa da izraz (3) približno 0,013 W/m K. Dejansko se krogle zlože

2 SHORT REVIEW OF CONTRIBUTION OF HEAT TRANSFER MECHANISMS IN EVACUATED STRUCTURES

2.1 Solid conductance

There is complete analogy between heat flow in solids and electric current in metals. Models for solid conductance, based on simple constriction resistance theory and prolonged heat paths, give quite realistic agreement with measured values especially for powder or fiber materials. Unfortunately, they are compressed substantially under atmospheric pressure in many cases which means increase of conductivity. A major part of heat transfer reduction in powders can be explained by a simple model of Hertz contacts between smooth elastic spheres (with different radii r , moduli of elasticity E and Poisson numbers μ). During the action of force F , real contact is formed over relatively small round area with radius r_c , named Hertz radius, calculated from:

At the right, effective values for curvature and elastic modulus E^* are used for the brackets at the left.

Constriction represents heat limiting element, contact resistance. It's inverse value, contact conductance, can be easily given from a basic electrical calculation as the product of the Hertz radius and the effective conductivity of the material, constituting spheres:

Let the external pressure p be applied to the spheres positioned in simple cubic lattice. There can be positioned n spheres per length L , while force per sphere is proportional to it's area. Conductivity of spheres arranged in cubic lattice is then from (1) and (2), (pressure due to their own weight is neglected) given by the simple relation:

The result is interesting, since there is no dependence on spheres diameter. For the glass with the lowest value among suitable materials and with $E^* = 7 \cdot 10^{10}$ Pa equation (3) gives $\lambda_{solid} = 0.013$ W/m K.

v redkejši sestav od predpostavljenega kubičnega, zato je povprečna prevodnost po samem nasutju še nekaj manjša. Koreksijski člen, potreben za opis poroznosti, prinese dodatno znižanje za približno polovico [11].

2.2 Sevanje

Opis prenosa topote s sevanjem je elementaren le med ravnima črnima stenama v vakuumu, ko veljajo Planckov, Stefanov in Wienov zakon. Kot črno telo se vedejo le močno segrete snovi.

V vakuumskih izolirnih strukturah, devarjih in superizoliranih posodah, se tanke kovinske plasti z enakomerno nizko odbojnostjo uporabljajo kot zrcala, postavljena pravokotno na smer toplotnega toka. Zaradi dolgega dosega fotonov med stenama, gradient v snovi ne obstaja, kar pomeni, da lahko reži dane debeline pripišemo prek izmerjenega koeficiente prehodnosti k le navidezno prevodnost. V primeru selektivno odbojnih površin je teoretičen opis prenosa topote zelo zahteven že za preprosto geometrijsko obliko.

V mikroporoznih snoveh je razširjanje termičnega sevanja namesto z zrcali oteženo s sisanjem in absorpcijo. Delež sevanja je v podatku za dan tip materiala določen s kombinacijo spektroskopskih in kalorimetričnih metod. Način razširjanja je zaradi kratkega dosega sevanja podoben difuziji, zaradi česar lahko snovi zares pripišemo delež, ki ga imenujemo analogno sevalna prevodnost. Ta se zaradi močne odvisnosti od temperature v smeri prevajanja močno spreminja, zaradi česar se spreminja tudi lokalni temperaturni gradient.

Močna odvisnost od temperature skromne sevalne deleže evakuiranih struktur obej opisanih tipov pri nizkih temperaturah spremeni v prevladujoče pri velikih.

2.3 Prispevek prevajanja plina

Zaradi večinskega prispevka plina k toplotni prevodnosti običajnih izolirnih materialov, si oglejmo nekaj fizikalnih osnov, ki pojasnijo pomen in potrebno znižanje tlaka. V termodinamiki zadoščajo za opis stanja plina podatki o temperaturi, tlaku in gostoti, ki jih povezuje splošna plinska enačba, ki velja tem bolj natančno, čim bolj je plin razredčen.

In fact, spheres are in reality positioned in less dense packing, which further reduces conductivity. Another correction for porous material further decreases cited value for almost a half, [11].

2.2 Radiative transfer

Radiative heat transfer is simple to describe only for simple geometry between black parallel planes in vacuum, when Planck's, Stefan's and Wien's laws hold, but only very hot solids behave like black bodies.

In evacuated insulating structures, dewars in SI vessels uniformly highly reflected metal surfaces are used as heat reflectors mounted perpendicular to direction of heat flow. Due to the long range of photons between the walls, a thermal gradient in the gap does not exist. This means that the quantity related to heat transferred through the gap, with analogy to material of the same thickness, can be only apparent conductivity. In the case of selective reflecting surfaces, theoretical description of heat transfer becomes complicated even for a simple geometry.

In microporous dispersed materials, thermal radiation is damped, instead of by mirrors, by internal scattering and absorption. The amount of transferred energy through a particular material is determined by combined spectroscopic and calorimetric measurements. Heat spreads through such media with diffusion due to the short range of thermal photons which enables to describe, for sufficiently thick samples, the so called radiative conductivity. Due to its temperature dependence, which varies greatly along a thermal path, the local thermal gradient must variate, too.

Strong thermal dependence can change radiative part at low temperatures to prevailing one at high temperatures in both types of evacuated structures.

2.3 Gaseous conductance

Since the gaseous conductance represents a major part of total conductance in insulating materials at atmospheric pressure, some physical phenomena about gas transfer theory which relates decrease of conductance by pressure reduction, are given. In thermodynamics, there are three basic quantities which are needed to describe the state of a gas: temperature, density and pressure, related by the ideal gas law, which holds better at lower pressures.

Nekatere od osnovnih količin, ki se pojavljajo pri prenosnih pojavih v plinu, je treba obravnavati skupaj z velikostjo opazovanega sistema. Pomožna veličina, Knudsenovo število, $\text{Kn} = L_g/d$. L_g - povprečna prosta pot, d - je karakteristična dimenzija, (npr. premer cevi), je eden od parametrov, ki natančneje opredelijo način prenosa energije. Plin, ki se nahaja v majhni zaprti prostornini, se zaradi pogostejših interakcij s posodo obnaša drugače kakor isti plin, ki je pri istem tlaku v veliki posodi. Oglejmo si v preglednici 1 povprečne proste poti za zrak v neomejeni prostornini v odvisnosti od tlaka pri sobni temperaturi.

Preglednica 1. *Povprečne proste poti molekul zraka v odvisnosti od tlaka pri temperaturi 300K*

Table 1. *Mean free paths of the air molecules as a function of the pressure at 300K*

$p(\text{mbar})$	$L_g(\text{m})$
10^3	$5 \cdot 10^{-8}$
1	$5 \cdot 10^{-5}$
10^{-3}	$5 \cdot 10^{-2}$
10^{-6}	50

Zamislimo si, da je plin zaprt med razsežnimi vzporednimi steni na razdalji d , vsaka na svoji temperaturi T_1 in T_2 . Za obravnavanje so zanimiva tri območja vrednosti Kn :

1) ($L_g \ll d$, $\text{Kn} \ll 1$). povprečna prosta pot molekule med molekulami L_g je dosti krajsa od razdalje med stenama. Toplotno prevodnost plinu (brez konvekcije) lahko pripisemo in jo izrazimo:

$$\lambda_{\text{gas}} = \frac{1}{3} \cdot \rho \cdot c_v \cdot v_a \cdot L_g = A \cdot \sqrt{\frac{T}{M}} \cdot L_g \cdot p \quad (4).$$

kjer so: ρ - gostota plina, c_v - specifična toplota pri konstantni prostornini, v_a - povprečna termična hitrost molekule, ki izhaja iz Maxwellove porazdelitve hitrosti, p - tlak, M - molna masa plina.

V desnem izrazu so v konstanti A zbrane količine, ki so manj bistvene, preostale pa so zapisane tako, da je nazorneje razvidna odvisnost od temperature in molne mase (vzrok za polnjenje pen s težkimi plini). Za ujemanje z merskimi vrednostmi realnih plinov je treba obrazec nekoliko popraviti.

Trki med steno in molekulo se dogajajo le v neposredni bližini sten, v medprostoru je večina trkov med molekulami. Temperatura in gradient v vsem prostoru sta določljiva, četudi težko merljiva. Toplotna prevodnost je sorazmerna zmnožku

Some of the basic quantities, which are necessary to describe transport phenomena in a gas, must be treated together with the size of the system. The derived quantity, Knudsen number, $\text{Kn} = L_g/d$. L_g - mean free path, d - characteristic length of the system (for example tube diameter), is one of the parameters which describe the state of the gas and transport phenomena. The same gas at the same temperature behaves differently in a small enclosure than the same gas in a large enclosure due to a different interaction with the walls. The mean free paths of the air molecules at room pressure is a function of the pressure in a very large volume are given in table 1.

Let the gas be enclosed between two parallel walls at distance d each at its own temperature T_1 and T_2 . Three regions of Kn values can be treated:

1) ($L_g \ll d$, $\text{Kn} \ll 1$), mean free path between molecules L_g is much shorter than separation of the walls d . Thermal conductivity of the gas is well defined and can be written as:

where: ρ - gas density, c_v - specific heat at constant volume, v_a - mean thermal velocity of molecules, which follows from Maxwellian distribution, p - pressure, M - molecular mass of particular gas.

On the right hand side, less important numerical factors are written in A , while the others are written so, that their temperature dependence and relation to molecular mass are seen more explicitly, (dependence on molecular mass explains the low conductivity of PU foams expanded with CFC gases). Some minor corrections are needed in above equation for full correlation with measured values.

Most of the interaction in the gas occurs between molecules and only a minor part between molecules and the walls. In the whole space, temperature and gradient are defined (even if they can not be measured so easily). Thermal conductivity

povprečne proste poti in gostote (oz. tlaka), ki je v širokem območju tlakov konstanta (10 mbar do 1000 bar). Za zrak pri tlaku 1 bar in pri sobni temperaturi znaša $\lambda_{\text{zrak}} = 0,026 \text{ W/m K}$. Zniževanje tlaka v tem območju vse do tlaka nekaj mbar tako ne prinese zmanjšanja prevodnosti plina.

2) ($L \gg d$, $Kn \gg 1$) - povprečna prosta pot je dosti daljša od razdalje med stenama. Termične prevodnosti kot fizikalne lastnosti plinu ne moremo pripisati. V medprostoru temperaturni gradient namreč ne obstaja. Mehanizem prenosa toplote je takrat odvisen od prilagodnega koeficiente obeh sten, ki pove, kolikšen del energije molekula z dano hitrostjo preda steni (se prilagodi njeni temperaturi). Število trkov je sorazmerno tlaku in korenju iz srednje temperature. Če gostoto toka delimo z razdaljo med stenama, lahko reži sicer pripšemo analogno veličino: navidezno ali nepravno prevodnost. Formalizem obravnavanja prenosa toplote razredčenega plina in sevanja v evakuirani reži sta si ob primerjavi analognih količin zelo podobna.

Predpostavimo, da je reža izčrpana do tlaka, ko velja pogoj za molekularni režim. Gostoto toplotnega toka, ki ga prenese plin, določimo z obrazcem:

$$j_{\text{gas}} = \left(\frac{\gamma + 1}{\gamma - 1} \right) \cdot \sqrt{\frac{R}{8\pi MT}} \cdot \frac{\alpha}{(2 - \alpha)} \cdot (T_1 - T_2) \cdot p \quad (5)$$

pri tem pomenijo: γ - razmerje specifičnih toplot plina, R - splošno plinsko konstanto, T - srednjo temperaturo, α - prilagoditveni koeficient (veličina, analogni emisivnosti pri sevanju) za vrsto plina in izbrano površino, predpostavimo, da je enak za obe površini.

Gostota toplotnega toka je odvisna od absolutne srednje temperature, od njune razlike, šibko odvisna je od α in za dvo- in večatomske molekule tudi od γ . Vrednost izraza (5), ki je za zrak pri $300 \text{ }^{\circ}\text{K}$ in razliki 1 K in pri tlaku 10^{-4} mbar le še $0,005 \text{ W/m}^2 \text{ K}$ pojasni nizek plinski del prevajanja v devarske posode.

3) ($L_g \approx d$, $Kn \approx 1$) v vmesnem območju med omenjenimi mejama, ko razdalja med ploščama d oz. premer pore v poroznem materialu d postaneta primerljiva s povprečno prosto potjo, lahko izraz za prevodnost podamo s približnim obrazcem:

$$\lambda = B \cdot \rho \cdot c_v \cdot v_a \cdot \left(\frac{L_g \cdot d}{d + L_g} \right) \quad (6)$$

kjer so v B so zajete številčne konstante.

Enačba pojasni pomen zniževanja tlaka na relativni skali povprečne proste poti v mikroporoznih materialih oz. strukturah, torej pomen čim manjših delcev oz. nastalih medprostorov pri praškastih

is so proportional to the product of mean free path and gas density (= pressure) which are constant over a range of pressure from 10 mbar to 1000 bar. Thermal conductivity of the air at room temperature and 1 bar is $\lambda_{\text{air}} = 0.026 \text{ W/m K}$. Pressure reduction in this region does noticeably decrease conductivity.

2) ($L \gg d$, $Kn \gg 1$) - mean free path is much longer than d . The thermal conductivity of the gas in a physical sense of its definition, cannot be described. In the mean space, thermal gradient does not exist. Heat transfer mechanism is dependent mostly of accommodation coefficient at both surfaces. It is the measure of the amount of energy which is transferred at collision from molecule to the wall. The rate of arrival of molecules is proportional to the pressure and the square root of the mean temperature. From the heat transfer rate divided by d , an analog quantity: apparent conductivity can be defined. Formally, the heat transfer rate across the evacuated gap, treating radiation or gas transfer with proper quantities, are both very similar.

Let the gap be evacuated to the pressure when the above condition for the molecular state of a gas holds. The heat transfer rate of the gas is then given by the equation:

where: γ - capacities ratio, R - universal gas constant, T - mean temperature, α - accommodation coefficient (i.e.analogous to emissivity of the surface) for a particular gas and wall combination, assumed to be equal at both surfaces.

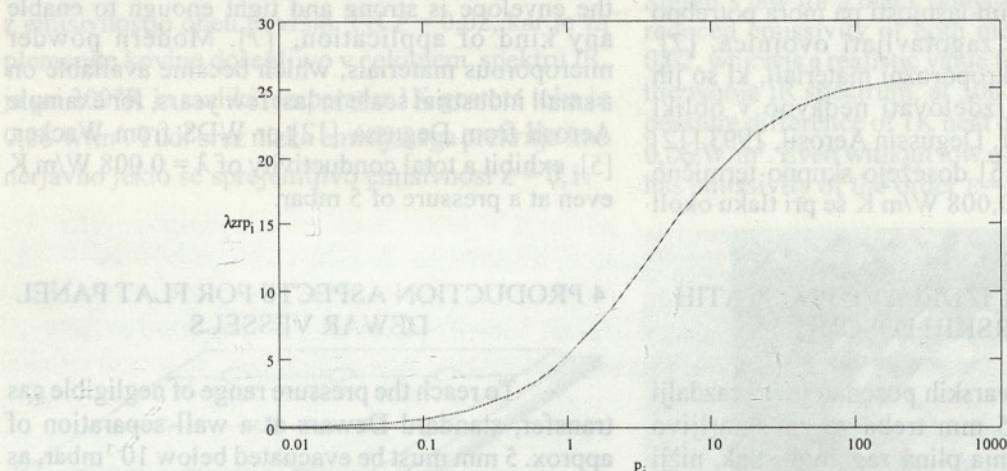
Heat transfer rate is dependent on mean absolute temperature and their difference, weak dependence is in α and for diatomic gases also in γ . The evaluation of eq. (5) for air at 10^{-4} mbar gives at 1 K difference only $0.005 \text{ W/m}^2 \text{ K}$.

3) $L_g \approx d$, $Kn \approx 1$ in the mean range between mentioned limits, when the mean free path and the distance between plates or mean pore diameter d become comparable, gas conductivity can be described by the approximate relation:

where B represents numerical factors.

Equation explains the importance of pressure reduction at the relative scale of mean free path in microporous materials. The mean pore diameter is determined by mean particle size. For example, a

materialih. Za primer materiala s povprečno velikostjo por $d = 0,05$ mm, (kar ga uvršča med makroskopsko razčlenjene materiale) lahko pojemanje toplotne prevodnosti plina s tlakom iz enačbe (6) nazorneje prikažemo grafično (sl. 1). V aerogelih z $d \approx 50$ nm bi bila krivulja premaknjena dokaj v desno.



Sl.1. Pojemanje prevodnosti plina (mW/K) v strukturi s povprečnim premerom pore $0,05\text{mm}$ v odvisnosti od tlaka mbar. Pri večanju tlaka velja enačba (4), pri nadaljnjem zniževanju tlaka se navidezna prevodnost linearno znižuje po enačbi (5)

Fig. 1: Decreasing of air conductivity (mW/mK) with internal pressure in a porous material. The curve represents the case where the mean pore diameter is $d = 0.05$ mm. At high pressure, value is given by eq. (4), while at lower pressure, apparent conductivity decreases linearly according to eq. (5).

Iz podanih primerov je razvidno, da je v makroskopsko razčlenjenih izolacijskih materialih oz. vakuumskih posodah za zmanjšanje prevajanja plina na zanemarljivo vrednost treba ustvariti srednji vakuum. Čim bolj pa je struktura mikroporozna, tem nižje so zahteve za preostali tlak. To je seveda privlačni vidik mikroporoznih praškastih materialov. Ne smemo pa spregledati ogromne fizične površine, ki jo ima razčlenjeno zgrajen material in dosega do $900\text{ m}^2/\text{g}$ [11]. Tako velike površine ne moremo zlahka razpliniti, zato je vzdrževanje stabilnega tlaka vseeno zahtevno. Varno ravnanje s temi materiali, ki so hidroskopični in se močno prašijo, vstevši transport, pripravo panelov, evakuiranje itn., pomeni tehnološki izziv, rešen v industrijskem merilu šele pred nedavnim.

Materiala s tako fino strukturo, ki bi omogočala minimalno prevajanje plina na račun mikroporoznosti v atmosferskem tlaku, kar je teoretično mogoče, še ni uspelo pripraviti. Strukture z danes največjo mikroporoznostjo (98%), so monolitni aerogeli, $\rho = 1$ do $2\text{kg}/\text{m}^3$, odkriti sicer že

material with a mean pore diameter $d = 0.05$ mm, (which belongs to macroscopically dispersed materials) the decrease of conductivity, given by eq. (6) can be represented graphically, Figure 1. In aerogel, where $d \approx 50$ nm, the curve for the same figure would lie far more to the right.

From the above examples, it may be seen that in macroscopically dispersed materials, or for the macroscopic gap in Dewars, gas conductivity drops to a negligible value in the fine vacuum range. By increased microporosity, higher residual pressure is allowed. This is an attractive part of the use of microporous powder materials. At the same time, their enormous internal surface can not be neglected since it can increase the value to $900\text{m}^2/\text{g}$ [11]. Such great surfaces are not easy to be outgassed sufficiently to maintain stable low pressure. Safe handling of these materials, which are hydroscopic and very dusty, including transportation and panel production, evacuation etc, was undoubtedly a technological challenge, only recently solved.

Theoretically, it would be possible to prepare the structure with so small a pore diameter whereby the gas conductivity would be negligible even at atmospheric pressure. The structure with the highest known microporosity is monolithic aerogel (void fraction 98 %) with a density of only $\rho = 1$ to $2\text{kg}/\text{m}^3$, discovered in the thirties. With controlled

v tridesetih letih. Z nadzorovanim sušenjem gela silicijeve kisline pri pogojih nadkritične temperature ostane krhek skelet s premerom por v območju 50 nm. Minimalno prevodnost plina v njem dosežemo že pri 100 mbar. Izredna krhkost, higroskopičnost in še relativno visoka cena zaradi počasnega sušenja močno omejujejo širšo uporabo. Zaradi prosojnosti je izredno privlačen za aktivne in pasivne solarne sisteme, zaradi opisanih lastnosti pa mora potrebno trdnost in tesnjenje zagotavljati ovojnica, [7]. Sodobni praškasti mikroporozni materiali, ki so jih začeli maloserijsko izdelovati nedavno v obliki evakuiranih plošč, npr. Degussin Aerosil, 1993 [12] in Wackerjev WDS [5] dosežejo skupno termično prevodnost okoli $\lambda = 0,008 \text{ W/m K}$ še pri tlaku okoli 5 mbar.

4 MOŽNOST IZDELAVE PLOŠČATIH DEVARSKIH POSOD

V običajnih devarskeh posodah je pri razdalji med stenama okoli 5 mm treba za zanemarljivo majhen delež prevajanja plina zagotoviti tlak, nižji od 10^{-3} mbar , preglednica 1 in slika 1. Zahteva je nedvomno resnejša od zahtev za mikroporozne materiale, vseeno pa ne takšna, da bi se je ne dalo uresničiti, če bi se pokazale njene prednosti.

Potrditev te trditve je napredek pri delu dveh skupin raziskovalcev, ki sta se zadnjih nekaj let ukvarjali s prozornimi steklenimi [1] in [6] oz. tankimi kovinskimi strukturami [2] in [3]. Delež prevajanja po trdni snovi je zmanjšan namesto z dispergiranim finim nasutjem z diskretnim podporjem. Rezultat dela prvih dveh skupin je vakuumnska zasteklitev s pravokotno prehodnostjo $k = 0,5 \text{ W/m}^2\text{K}$. Rezultat druge skupine pa so tanki kovinski paneli z navidezno prevodnostjo pod $\lambda = 0,005 \text{ W/mK}$.

V letu 1993 je na Fakulteti za strojništvo v Ljubljani stekel manjši raziskovalni projekt študija karakteristik ploskovnih evakuiranih elementov in preučitev možnosti njihove izdelave.

Oglejmo si ploščato devarske posodo s tankima kovinskima stenama, ki ju lokalno podpirajo diskretne podpore, izdelane iz stekla ali keramike (sl. 2). Podpore morajo dajati toplotnemu toku čim večjo upornost, oblika na mestu dotika s folijo pa mora biti dovolj velika in zaobljena, da je lokalni tlaki in napetosti ne poškodujejo. Vakuumnska zahteva je, da morajo imeti čim manjšo lastno notranjo površino. Najprimernejši material za ovojnico, glede mehanskih, vakuumskih in toplotnih lastnosti, je folija iz nerjavnega nizkoogljičnega jekla ($\lambda_{\text{solid}} = 15 \text{ W/m K}$). Debela mora biti med 0,1 in 0,15 mm, kar še omogoča uporabo specialnih tehnik vakuumsko tesnega varjenja. Prečno prevajanje je pri izbrani debelini 0,15 mm pri dovolj razsežni plošči še sprejemljivo majhno.

drying of gel silica acid at oversaturated temperature brittle skeleton with a mean pore diaeter in the range of 50 nm. Conductivity becomes negligible even at 100 mbar. It's brittleness, hygroscopic behavior and high price due to a slow drying process, limit wider use. It is translucent and so very suitable for active and passive solar systems, but due to it's mentioned characteristics, it is very important that the envelope is strong and tight enough to enable any kind of application, [7]. Modern powder microporous materials, which became available on a small industrial scale in last few years, for example Aerosil from Degussa [12] or WDS from Wacker, [5], exhibit a total conductivity of $\lambda = 0.008 \text{ W/m K}$ even at a pressure of 5 mbar.

4 PRODUCTION ASPECTS FOR FLAT PANEL DEWAR VESSELS

To reach the pressure range of negligible gas transfer, standard Dewars at a wall separation of approx. 5 mm must be evacuated below 10^{-3} mbar , as seen from Table 1 and Figure 1. The demand is much more serious than for microporous materials, but it could be technically fulfilled if some benefits could be expected.

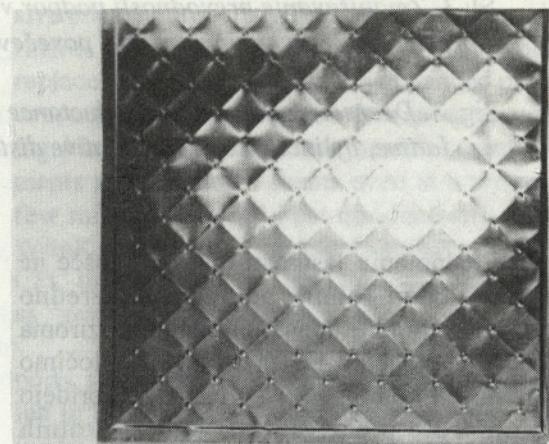
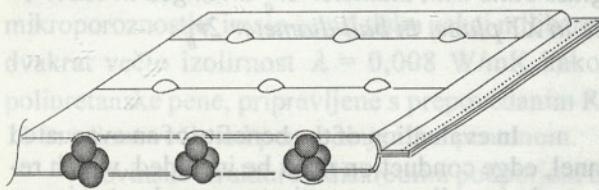
Above estimations were confirmed by the progress of the research of two groups, the first one analyzed the possibilities of flat evacuated glazing, [1] and [6] while another studied ultra thin metal structures, [2] and [3]. Solid conductance is reduced, instead of with dispersed materials, by discrete spacers made from bulk material. The result of the first is the glazing with 0.1mm gap with $k = 0.5 \text{ W/m}^2\text{K}$, while another one prepared samples with $\lambda = 0.005 \text{ W/mK}$.

In 1993 at Faculty for Mechanical Engineering in Ljubljana, a project to analyze and to improve the above values for thin metal structures.

Such a metal structure, composed of two thin metal foils, supported by an array of discrete glass or ceramic beads, is seen on figure 2. To minimize heat flow, supports must have the highest thermal resistance, while they must be rounded enough that local tension does not damage the foil. Further demand regarding vacuum is their minimum internal surface. The best choice for the envelope material, relating mechanical, vacuum and thermal properties is low carbon stainless steel foil (AISI, S304) which has ($\lambda_{\text{solid}} = 15 \text{ W/mK}$). It's thickness is a compromise between the mentioned demands, mainly limited by the technology of high vacuum tight welding. Lateral conduction of the selected foil thickness of 0.15 mm is still tolerable.

Delež prevajanja podpor, plina in sevanje, ki določajo skupne lastnosti strukture, so določljivi vsak posebej, saj so skoraj neodvisni drug od drugega. Če predpostavimo, da je reža izčrpana do srednjega vakuma, velja za oceno deleža, ki ga prenese plin, enačba (5), torej je ta del zanemarljiv. Delež sevanja lahko izračunamo s Stefanovo formulo, popravljeno z emisivnostjo obeh površin. Pri $\varepsilon = 0,02$, kar je za plemenite kovine dosegljivo v celotnem spektru IR, je pri 300 K in razliki temperatur 1 K gostota toka le $0,06 \text{ W/m}^2$. Tudi brez nizko emisijskega prekritja ima nerjavno jeklo še sprejemljivo emisivnost $\varepsilon = 0,1$.

Contribution of conduction of supports, residual gas and radiative transfer, which determine properties of the structure, can be calculated separately since they are almost independent of each other. When it is supposed that the gap is evacuated down to a fine vacuum range, then it follows from Eq. (5) that the gaseous contribution to heat transfer is negligible. Radiative transfer can be calculated from Stefan's law for a black body with correction for the reduced emissivity of both metal surfaces. For $\varepsilon = 0,02$, which is a realistic value for noble metals across the whole IR spectrum, at 300 K this means a temperature difference of 1 K heat current density of only $0,06 \text{ W/m}^2$. Even without low e-coating stainless steel has emissivity of the order $\varepsilon = 0,1$.

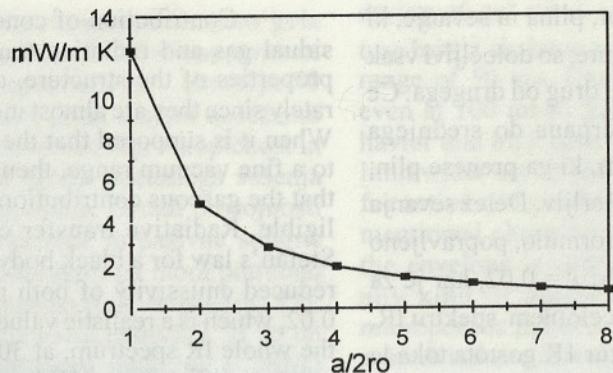


Sl.2. Shematski prikaz vakuumskega panela (levo) in slika vzorca površine $0,1 \text{ m}^2$ v fazi izdelave (desno). Za testni panel so izbrane podpore krogle

Fig. 2: Schematic view of a vacuum insulation panel (left) and a figure of a panel of area $0,1 \text{ m}^2$ during assembling (right). For the test panel supports are single spheres

Preostane nam še ocena, na kakšno vrednost lahko zmanjšamo prevajanje podporja. Zanj nimamo druge omejitve, le da je preprosto, stabilno in tehnično izvedljivo. Za analizo naj bodo podpore, sestavljene iz krogel, za katere je mehanika kontakta najbolje poznana in privzeta v izpeljavi enačbe (3). Če za trenutek odmislimo stabilnost, se lahko vprašamo, koliko krogel iz nasutja smemo odstraniti, da bi preostale vzdržale zunanjji tlak. Za steklo dosežemo mejo trdnosti pri medsebojni razdalji krogel v kvadratni mreži, ki je enaka 7 do 8-kratnemu premeru. Prevodnost po trdni snovi bi bilo, s takimi hipotetičnimi podporami, ki jih sestavljajo steklene krogle v dveh plasteh (sl. 2), mogoče znižati na $\lambda = 0,001$ do $0,002 \text{ W/mK}$, enačbi (2) in (3). Prikaz zmanjševanja prevodnosti na račun zvečevanja relativne razdalje med krogli v preprosti kubični mreži je na sliki 3. Reža ostane tako dokaj prazna, zaradi česar jo je bistveno laže evakuirati, kakor če bi bila nasuta s kroglicami, občutno je zmanjšana tudi masa. Podobne vrednosti dobimo tudi s cirkonovo keramiko, pri kateri se nekaj večja prevodnost kompenzira z večjim elastičnim modulom.

The last estimation for supports conductance can be made with additional limitation, that supports must be: simple, stable and that they can be realized technically. Calculation is based on simple geometry of touching balls due to well known mechanics, already mentioned in derivation of Eq. (3). Neglecting for the moment the problem of stability, we can ask how many balls from the cubic lattice can be taken away so that the remaining balls would still sustain the atmospheric pressure. For the case of glass balls, the maximum distance is 7 to 8 ball diameters. Solid conductance for such hypothetical supports arranged in two layers would be in the range of $\lambda = 0,001$ to $0,002 \text{ W/mK}$, followed from Eq. (2) and (3). The decrease of solid conductivity by increasing ball to ball diameter in cubic array is given in Fig. 3. The gap in this case remains relatively empty, which means easier evacuation and less weight compared to the case of all the balls being present. A comparable figure than for the glass balls are obtained for zirconia, when a slightly greater solid conductivity is compensated by a higher value of elastic modulus.



Sl. 3. Zmanjševanje prevodnosti podpor v $mW/m\ K$, ki jo predstavlja dve plasti krogel s premerom $2r_0$ v kubični mreži s povečevanjem medsebojne razdalje v enotah $2r_0$

Fig. 3. Decrease of the solid conductance of glass balls with diameter $2r_0$ arranged in cubic lattice, by increase of the relative distance in XY plane, in ball diameter $2r_0$

Pri vrednotenju lastnosti opisane plošče ne smemo spregledati robnih pojavov, ki izredno izolirnost pri majhnih dimenzijah izničijo oziroma vsaj zasenčijo. Pametno je, da za panel določimo mesto vgradnje v kombinaciji z elementi, ki pridejo v stik z njim. Že prekrivanje ravnih ali kotnih elementov, ko si zamislimo gradnjo oglatih prostorskih posod, odpravi velik del pomanjkljivosti zaradi robnih pojavov. Numerična simuliranja, ki smo jih opravili sicer za ravninski primer, kažejo, da je pri prekrivanju panelov za nekaj centimetrov, če so ti široki vsaj 0,5 m, izolirnost minimalno zmanjšana. Podrobnejši izračun prevajanja ovojnice in njen vpliv na izolacijske lastnosti vakuumskih panelov, pri katerih je podporje mikroporozen prah, je v [5]. Polimerna ovojnica debeline 0,2 mm z Al folijo debeline 0,01 mm, kakršna zagotavlja dolgotrajno uporabnost je glede prečnega prevajanja primerljiva z 0,15 mm debelo folijo iz nerjavnega jekla, kakršno smo uporabili pri izdelavi vzorcev.

Vakumske zahteve za dolgotrajno uporabnost panelov so nedvomno resnejši del težav, ki jih je potrebno rešiti v fazi raziskav in razvoja. Mednje sodi izbira postopkov priprave, predobdelave in čiščenja elementov pred procesiranjem. Dopustno puščanje je v razredu kovinskih posod UVV in zataljenih steklenih elektronk, to je 10^{-12} mbar l/s. Med tehnikami varjenja in lotanja smo se po testih na miniaturnih vzorcih odločili za nekaj vrst spojev. Črpalo bakreno cev smo na prehodni del cevi iz nerjavnega jekla trdo pritolali, na drugi strani pa lasersko privarili na folijo. Glavni šivni zvar med folijama smo opravili na industrijski napravi za

In evaluation of the benefits of an evacuated panel, edge conduction must be included, which reduces its excellent properties to a moderate size or diminished them at small size. It is sensible to plan where such a panel can be mounted in realistic design of device regarding other elements. Simple covering of panels (2D) or edge panels (3D) when building an insulating square box reduces edge effects drastically. Our numerical simulations for the 2D case, which are compared with similar simulations for evacuated panels, show that by covering the panels for some cm (at a panel width of 0.5m), their performance is only slightly reduced. Further treatment of the influence of the envelope to overall performance of a refrigeration unit (based on a 2D model) is also given in [5].

Vacuum requirements for long term use of vacuum panels of the previously mentioned type are undoubtedly a very serious problem, which must be solved during the R&D phase. Appropriate selection of material, careful treatment (mainly cleaning) of elements during all steps before vacuum processing. A tolerable leak rate for such panels is in the range, such as for UHV metal chambers and electronic tubes made of glass, is 10^{-12} mbar l/s. Among known techniques of welding and brazing, we chose only a few of them, which were selected after preliminary tests on sample probes. The pumping tube is made of OFHC grade copper. At one end, it was brazed to a short stainless steel tube of equal diameter which enabled us to weld it by laser to the foil. The other end (pump side) was connected by a joint where copper is pressed in a cone to form a cold weld. For the main weld at the edge of the two foils, roll resistance welding was chosen, provided by industrial machine

kolutno uporovno varjenje v Metalflex (Tolmin). Po črpanju je treba bakreno cev hladno zavariti. Trenutno potekajo meritve naraščanja tlaka v testnih vzorcih s površino $0,1\text{m}^2$, ki so bili med črpanjem segreti na določeno temperaturo, [9]. Okvirni podatki za izdelavo so bili izračunani na podlagi ocen difuzije vodika, razpoložljive hitrosti črpalne povezave itn.

4 SKLEP

Pri zamenjavi freonov z neškodljivimi plini (ogljikovodiki) se izolirnost poliuretanskih pen opazno poslabša. Med možnimi, vendar občutno izboljšanimi nadomestili, so v razvoju najdlje izpraznjene praškaste strukture. Z danes doseženo mikroporoznostjo imajo že pri tlaku nekaj milibarov dvakrat večjo izolirnost $\lambda = 0,008 \text{ W/mK}$ kakor poliuretanske pene, pripravljene s prepovedanim R-11 in trikrat večjo od pen, polnjenih s pentanom.

Kovinske strukture z diskretnim podporjem in še manjšo prevodnostjo, ki smo jih začeli raziskovati na Fakulteti za strojništvo v Ljubljani, so v zgodnejši fazi razvoja in je zato napoved o možnosti njihove uveljavitev še tvegana. Naše raziskave kažejo na možnost doseganja navidezne prevodnosti, pri omejeni debelini, pod $\lambda = 0,003 \text{ W/mK}$ [8]. Narejen je bil teoretični model, opravljene so bile analogne električne meritve stičnega upora na fizičnem modelu, [10]. Trenutno potekajo meritve vakumske tesnosti in projekcija dolgotrajnega prirastka tlaka. Preučiti je treba tehnologijo izdelave, ki bi obremenjeni ovojnici zagotovljala potrebni vakuum načrtovanih 10 let. V primerjavi z običajnimi izolacijskimi materiali ali evakuiranimi praškastimi ploščami s polimerno ovojnicico, so lahko plošče iz nerjavnega jekla hkrati že okrov naprave, ki jo želimo izolirati.

Zahvala

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(Metalflex, Tolmin). After pumping, the copper tube is cut to form a cold weld. Currently, pressure rise is measured in the test panels with an area of 0.1m^2 , which were baked during the pumping [9]. The duration and temperature of baking were calculated according to available data of hydrogen diffusion, effective pumping speed etc.

4 CONCLUSIONS

Replacement of CFC compounds as expanding gases in polyurethane foams with non aggressive ones (hydrocarbons) is manifested by a deterioration insulating properties. Among possible replacement materials with enhanced properties, evacuated microporous powders seem very promising. Materials, available today, exhibit great improvements against blown foams even at a pressure of a few milibar. Overall heat conductivity $\lambda = 0.008 \text{ W/mK}$ makes these structures twice as efficient as CFC blown foams or almost three times as efficient as "green", pentane filled foams.

Metal evacuated structures with discrete supports, studied at the Faculty of Mechanical Engineering in Ljubljana, could exhibit even higher insulating values, but are at the moment still in earlier stage of development. Our results show that structures even below $\lambda = 0.003 \text{ W/mK}$ could be prepared at some limited thickness, [8]. A theoretical model and measurements of contact resistance of a single electric analog contact between the sphere and the foil were made [10]. Currently, long term pressure rise due to leaks and outgassing are running. The selected technology must guarantee that the insulating vacuum can be preserved for at least 10 years. The difference of present structure with a strong stainless steel envelope is, in comparison to powder filled panels with a polymere envelope, the possibility of applying them to the outer body of a device, which requires insulations.

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