

Control of insulating properties using flexible soft seals

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Abstract

This work analyzes and discusses analytically a method of controlling the insulating properties of an assembly. It establishes the feasibility of utilizing gas layers within the insulating assembly separated by flexible soft seals. The volumetric thermal expansion of the main gas layers within the insulating assembly are determined taking into consideration the variation in the gas pressure due to the elastic behavior of the supporting flexible soft seals. It was found that the volumetric thermal expansion of the main gas approaches its isobaric condition value as the main gas layer thickness decreases. Also, it is found that insulating properties are enhanced when the main gas has a minimum thermal conductivity and when relatively high temperatures are experienced. However, insulating properties deteriorate at large temperatures when the main gas has a relatively large thermal conductivity. Finally, advanced insulating assemblies with maximized insulating properties are proposed.

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1. Introduction

Insulating materials are used in most industrial applications in order to conserve the thermal energy. For example, they are widely used as one of the layers within slab walls of the residential buildings in order to minimize thermal loads of the air conditioning systems [1]. Furnaces are usually surrounded by thick insulating materials to reduce thermal losses [2]. At severe thermal conditions, bulky insulating material is required to reduce thermal losses. However, these additional insulating material are not usually required when thermal conditions are normal leading to over designed and expensive thermal systems.

Light weight fiber materials are widely used in insulating materials for high temperature applications like thermal insulations in ovens or heat exchangers [3].

When gases with lower thermal conductivities are filling the volume between the fiber material, the insulating properties of the insulator is enhanced [3]. Another method which can be utilized to enhance the insulating properties of thermal insulators is to take benefit of the volumetric thermal expansion property of gases. This will reveal construction of compact insulating assemblies that enhances insulating properties especially at large operating temperatures.

In this work, the thermal characteristics of an insulating assembly composed of substrates separated by gas layers are analyzed. The gas layers are supported by flexible soft seals in order to allow for volumetric thermal expansion of the main gas layer while the secondary one is vented to the atmosphere such that the secondary gas pressure remains constant. The volumetric thermal expansion of the main gas layer is determined analytically and correlated to the increase in the equivalent thermal resistance of the gas layers. Accordingly, enhancements in the insulating properties are found and determined for certain gases while deteriorations in the insulating properties are determined for a different family of gases.

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Nomenclature

A_S	surface area of the intermediate insulating substrate	R_{th}	thermal resistance of the gas layers
C_F	volumetric thermal expansion efficiency	R_{th0}	reference thermal resistance of the gas layers
h_c	convective heat transfer coefficient at the upper surface	T	average temperature of the main layer
h_o	reference thickness of the main layer	T_1	temperature at the lower surface of the main layer
K^*	stiffness of the supporting seal	T_o	reference main gas temperature
k_{ins}	thermal conductivity of insulating substrates	T_e	temperature of the upper surface facing of the surroundings
k_1	thermal conductivity of the main gas	<i>Greek symbols</i>	
k_2	thermal conductivity of the secondary gas	Δh_1	expansion of the main gas layer
m_1	mass of the main gas	η_R	dimensionless increase in the resistance of the gas layers
p_{atm}	pressure of the surrounding		
q	heat flux		
R_1	main layer gas constant		

2. Theory

Generally, thermal losses increase at large working temperatures. The goal here is to establish a new material assembly that will have desirable insulative attributes even at high working temperatures. This assembly shown in Fig. 1 is composed of the following from bottom to top: (1) a heated substrate, (2) a layer of gas that has a very low thermal conductivity such as Xenon (the main gas layer), (3) a thin layer of an insulating substrate, (4) a secondary layer of another gas that has a lower thermal conductivity like air (needs to be larger than that of the first layer and is open to the outside environment) and (5) a top insulating substrate. The two gas layers along with the intermediate insulating substrate are connected together by flexible soft seals. Both the heated substrate and the upper insulating substrate are fixed while the intermediate insulating substrate is free to move as it is supported by flexible soft seals. In order to avoid melting of the seals at high temperatures, ordinary homogeneous soft seals can be replaced with closed-cell foams composed of mainly small air voids separated by sealed partitions that can

sustain high temperature. As such, the performance of the assembly can be improved to sustain high temperatures.

2.1. Operational principle

When the operating temperature (high temperature source) increases, the average gas temperature of the main layer increases. Accordingly, the volume of the main layer expands accompanied by a shrinkage in the secondary layer. As such, an increase in the equivalent thermal resistance of the insulating assembly can be attained as long as the thermal conductivity of the main layer is smaller than that for the secondary gas layer. It is worth noting that the heated substrate should have a relatively small thickness and a relatively large thermal conductivity so that the thermal expansion of the main layer is maximized.

2.2. Volumetric expansion in the main layer

Forces on elastic materials such as seals are usually proportional to the elongation of this material [4].

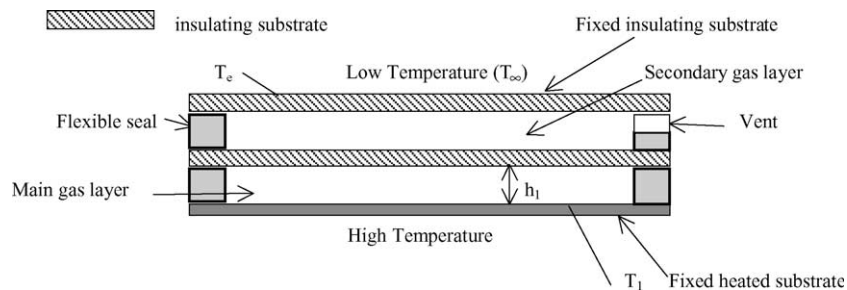


Fig. 1. An enhanced insulating assembly.

Accordingly, a force balance on the intermediate insulating substrate results

$$\frac{m_1 R_1 T}{A_S (h_o + \Delta h_1)} - p_{\text{atm}} = \frac{K^*}{A_S} \Delta h_1 \quad (1)$$

where T , K^* and A_S are the average temperature of the main gas layer, the stiffness of the supporting seals and the surface area of the intermediate insulating substrate, respectively. The quantities h_o and Δh_1 are the reference thickness of the main layer and the corresponding expansion in the main layer thickness, respectively. The first term on the left-hand side of Eq. (1) represents the pressure inside the main gas layer. The reference thickness h_o corresponds to the thickness of the main layer when the main gas pressure is equal to the atmospheric pressure. The parameters m_1 and R_1 are the mass of the main gas and the main gas constant, respectively. Eq. (1) can be solved for Δh_1 and the expansion is found to be

$$\frac{\Delta h_1}{h_o} = C_1 \left(\sqrt{\frac{C_2}{C_1^2} + 1} - 1 \right) \quad (2)$$

where

$$C_1 = \frac{(p_{\text{atm}} A_S) / (K^* h_o) + 1}{2} \quad (3)$$

$$C_2 = (m_1 R_1 T) / (K^* h_o^2) - (p_{\text{atm}} A_S) / (K^* h_o) \quad (4)$$

In order to maximize the expansion in the main layer which in turn results in better insulative properties, the parameter C_2 needs to be maximized. This can be accomplished by considering minimum values of $K^* h_o$ while the following relationship is preferred to be satisfied.

$$\frac{m_1 R_1 T}{p_{\text{atm}} A_S h_o} \gg 1 \quad (5)$$

The following parameters are considered for studying the sealing assembly: $K^* = 48\,000$ N/m, $A_S = 0.0036$ m² and $p_{\text{atm}} = 0.1$ MPa. The parameter $m_1 R_1$ is evaluated at the reference condition when the main gas pressure is equal to the atmospheric pressure. This condition which causes the expansion to be zero in Eq. (1) is assumed to be at $T = T_o = 283$ K and $h_o = 0.004$ m. This leads to

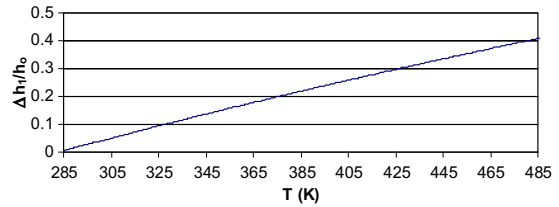


Fig. 2. Main layer expansion versus its temperature.

$m_1 R_1 = 5.088 \times 10^{-3}$ J/K. Accordingly, the relation between the volumetric thermal expansion of the main layer and its average temperature is illustrated in Fig. 2.

Eq. (2) reduces to the following linearized model for relatively low volumetric thermal expansion levels ($\frac{\Delta h_1}{h_o C_1} \ll 1.0$):

$$\frac{\Delta h_1}{h_o} \approx 0.5 \frac{C_2}{C_1} + O(\Delta h_1^2) = \frac{T - T_o}{T_o + \frac{K^* h_o^2}{m_1 R_1}} + O(\Delta h_1^2) \quad (6)$$

where T_o is the average temperature of the main gas layer at the reference condition. Note that the thermal expansion is zero when the main layer is kept at T_o . At this condition, the main layer thickness is h_o . The relative volumetric thermal expansion, $\Delta h_1/h_o$, approximated by Eq. (6) is similar to that for isobaric expansion with the average main gas temperature being increased by the parameter $\frac{K^* h_o^2}{m_1 R_1}$. This parameter will be denoted as ΔT_o .

The error associated with Eq. (6) is further reduced if $\frac{m_1 R_1 T_o}{K^* h_o^2} > 1$. The latter inequality means that the insulating system exhibits relatively large volumetric thermal expansion by having a small increase in the main gas pressure due to the elastic behavior of the seal. Fig. 3 illustrates the difference between the relative volumetric expansion expressed by Eq. (6) and that when the expansion is at a constant pressure. Fig. 3 shows that isobaric conditions provide favorable volumetric thermal expansion when compared to volumetric thermal expansion under linearly varying pressure as when seals are present.

The efficiency of the volumetric thermal expansion C_F of the main layer is defined as the ratio of the expansion

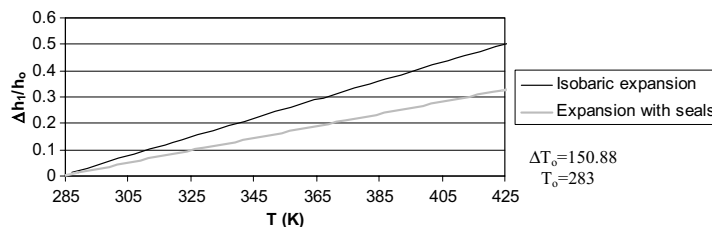


Fig. 3. Percentage volumetric thermal expansion for the conditions of isobaric expansion and expansion using a linearized model under linearly varying pressure.

Table 1
Volumetric thermal expansion efficiency C_F of the main layer versus ΔT_o

ΔT_o (K)	C_F ($T_o = 283$ K)
10	0.966
50	0.850
100	0.739
150.88	0.652

in the main layer when the seal is present to that when the expansion is under constant pressure. That is, it is expressed mathematically as

$$C_F = \frac{\Delta h_1}{(\Delta h_1)_{\text{isobaric}}} \quad (7)$$

where $(\Delta h_1)_{\text{isobaric}}/h_o = (T - T_o)/T_o$. For the linearized model shown in Eq. (6), the efficiency C_F will be

$$C_F \cong \frac{T_o}{T_o + \Delta T_o} \quad (8)$$

According to Eq. (8), the values of C_F which approaches unity as $\Delta T_o = \frac{k^* h_o^2}{m_1 R_1}$ decreases are tabulated in Table 1 for various ΔT_o .

2.3. Equivalent thermal resistance of gas layers

The equivalent thermal resistance of the gas layers during volumetric thermal expansion is given by

$$R_{\text{th}} = \frac{h_o}{k_1} + \frac{h_o}{k_2} + \Delta h_1 \left(\frac{1}{k_1} - \frac{1}{k_2} \right) \quad (9)$$

where k_1 and k_2 are the thermal conductivity of the main and the secondary gases, respectively. It is assumed that both gas layers have a similar thickness prior to thermal expansion equal to h_o . Based on Eqs. (1) and (3), the increase in the equivalent thermal resistance ΔR_{th} , the third part on the right of Eq. (9), is correlated to the relative expansion in the main layer according to the following relation:

$$\eta_R \equiv \frac{\Delta R_{\text{th}}}{R_{\text{tho}}} = \frac{\Delta h_1 (k_2 - k_1)}{h_o (k_1 + k_2)} \quad (10)$$

where R_{tho} is the equivalent thermal resistance of both layers prior to thermal expansion. The parameter R_{tho} is

the sum of the first two terms on the right of Eq. (9). When the parameter η_R is positive, the thermal resistance of the insulating assembly increases while it decreases as it becomes negative. Therefore, it represents the dimensionless increase in the thermal resistance. Table 2 shows various properties of different gases. According to Table 2, Xenon can be used to enhance the insulating properties while Helium is preferable to deteriorate the insulating properties especially at large operating temperatures as can be noticed from the last column in Table 2.

Fig. 4 shows the dimensionless increase in the gas layers equivalent thermal resistance when the main layer is charged with Xenon or Helium while the secondary layer is open to the atmosphere. Charging the main layer with Xenon can provide about 20 percent increase in the effective thermal resistance of the gas layers with an increase of the main layer temperature by 165 K. However, Helium can produce a deterioration in the insulating properties by about 25 percent with 165 K increase in the main layer temperature.

2.4. Heat transfer analysis

In the following analysis, it is assumed that the temperature at the lower side of the main gas layer is kept under T_1 (Fig. 1). The insulating substrates are assumed to have equal thicknesses and thermal conductivities which are equal to the reference thickness for the main layer h_o and k_{ins} , respectively. Accordingly, the thermal energy balance on the insulating assembly shown in Fig. 1 reveals the following relation for the temperature at the surface of the lower temperature side T_e and the heat transfer q , respectively:

$$T_e = \frac{(T_1 - T_\infty)/h_c}{\left(\frac{1}{h_c} + \frac{2h_o}{k_{\text{ins}}} + R_{\text{tho}} \left(1 + \frac{\Delta R_{\text{th}}}{R_{\text{tho}}} \right) \right)} + T_\infty \quad (11)$$

$$q = \frac{(T_1 - T_\infty)}{\left(\frac{1}{h_c} + \frac{2h_o}{k_{\text{ins}}} + R_{\text{tho}} \left(1 + \frac{\Delta R_{\text{th}}}{R_{\text{tho}}} \right) \right)} \quad (12)$$

where h_c and T_∞ are the convective heat transfer coefficient at the lower temperature side and the temperature of environment facing the lower temperature side,

Table 2
Various properties of proposed different gases at $T = 373$ and $p = 1$ atm

Main gas	k (W/m K)	ρ (kg/m ³)	R (J/kg K)	$(k_{\text{air}} - k)/(k_{\text{air}} + k)$
Xenon	0.0068	4.3	64.05	0.609
Krypton	0.011	2.75	99.78	0.4359
Helium	0.181	0.13	2077	-0.732
Neon	0.0556	0.66	412.1	-0.33
Argon	0.0212	1.3	209	0.138
Air	0.028	1.2	287	0

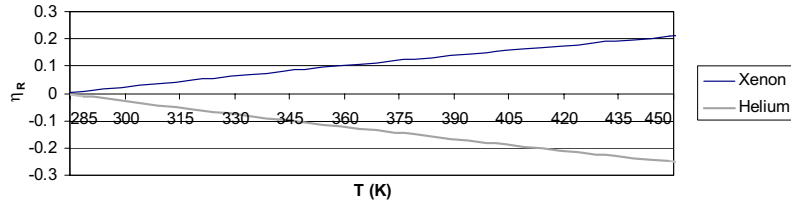


Fig. 4. Dimensionless change in the equivalent resistance of the gas layers for two different gases.

respectively. The surface area of the insulating assembly that faces the seal portion is relatively small. Therefore, the heat transfer through the seal portion is neglected in Eqs. (11) and (12).

For the previous example along with $h_c = 5 \text{ W/m}^2 \text{ K}$, $T_\infty = 275 \text{ K}$ and $k_{ins} = 0.04 \text{ W/m K}$, the temperature T_e as a function of T_1 is illustrated in Figs. 5 and 6, respectively. These figures also compare the temperature T_e for the case when the thermal expansion is encountered due to the presence of seals with the case where thermal expansion is not present (both gas layer thicknesses are equal to h_o for all values of T_1). Fig. 5 shows that insulating properties are enhanced when Xenon and soft seals are used and that T_e for this case is departing away down from the values corresponding to the case where the thermal expansion is not present. Also, this figure shows that the departure rates increase as the temperature levels increase.

Fig. 6 shows that insulating properties are deteriorated when Helium and soft seals are used. It is found in Fig. 6 that the departure of T_e for this case from the results corresponding to the case with no thermal expansion is in the direction of an increase in T_e . Thus, insulating properties are deteriorated at larger rates when Helium and

flexible seals are used especially at large operating temperatures. It should be noted that the thermal expansion of the main layer was computed at its average temperature. As such, an iterative procedure was implemented in generating Figs. 5 and 6 so that the found temperatures produce the employed thermal expansion of the main layer. Also, the volumetric thermal expansion that are used to develop Figs. 5 and 6 are evaluated from Eq. (2).

Fig. 7 shows a comparison of heat flux of the insulating assembly with Xenon as the main gas under two conditions: (1) in the presence of flexible soft seals and (2) when thermal expansion is not present and the thickness of the gas layers is h_o at all working temperatures. This figure shows a reduction in the heat flux when seals are introduced. It also shows that the reduction rate increases as the working temperatures increase indicating better insulating characteristics are achieved when soft seals are used to support the main gas layer while the secondary gas layer is vented. On the other hand, an increase in the heat flux is attained when soft seals are used to support the gas layer if it contains a gas with relatively large thermal conductivity such as Helium as shown in Fig. 8.

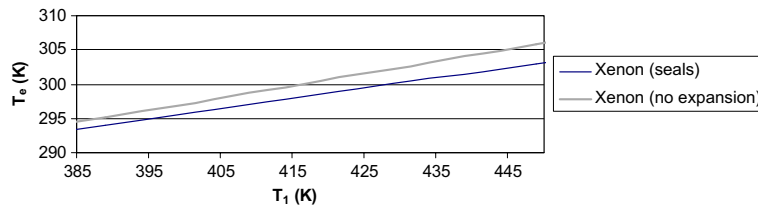


Fig. 5. Enhanced insulating properties using xenon and flexible insulating assembly.

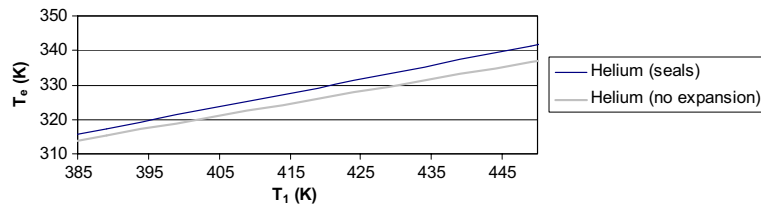


Fig. 6. Deteriorated insulating properties using helium and flexible insulating assembly.

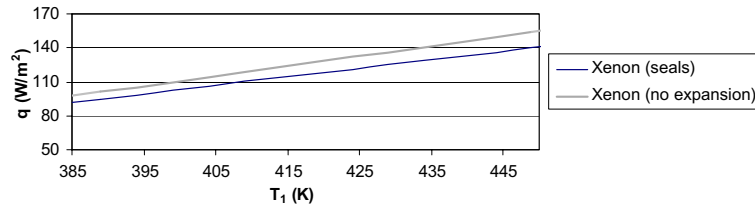


Fig. 7. Reduction of thermal losses at large operating temperatures using xenon and flexible insulating assembly.

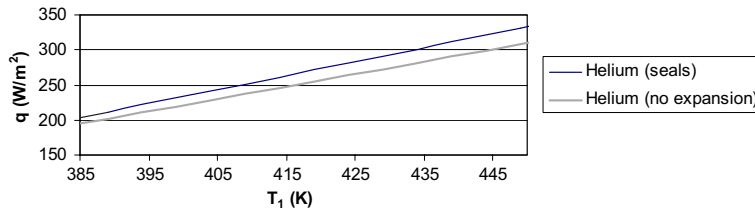


Fig. 8. Deterioration of thermal losses at large operating temperatures using helium and flexible insulating assembly.

2.5. Simplified correlation

For the insulating assembly shown in Fig. 1, heat transfer can be expressed by the following relation:

$$q = \frac{(T_1 - T_e)}{\left(\sum_{i=1}^2 \frac{(h_{ins})_i}{(k_{ins})_i} + \left(\frac{h_{o1}}{k_1} + \frac{h_{o2}}{k_2} \right) \left(1 + \frac{(k_2 - k_1)}{(k_2 + h_{o2}k_1/h_{o1})} \left(\frac{\Delta h_1}{h_{o1}} \right) \right) \right)} \tag{13a}$$

where $\Delta h_1/h_{o1}$ can be shown to be equal to the following:

$$\frac{\Delta h_1}{h_{o1}} = \left(\frac{T_o + \Delta T_o}{2\Delta T_o} \right) \left[\sqrt{\frac{4(T_1^* - T_o)\Delta T_o}{(T_o + \Delta T_o)^2} + 1} - 1 \right] \tag{13b}$$

The quantities h_{o1} , h_{o2} , $(h_{ins})_i$, $(k_{ins})_i$ are the reference main layer thickness, reference secondary layer thickness, thickness of the i th insulating substrate and the thermal conductivity of the i th insulating substrate, respectively and that T_o is the main layer temperature that causes the main gas pressure to be equal to the atmospheric pressure. The parameter T_1^* represents the average main layer temperature which can be measured experimentally or determined theoretically using an it-

erative scheme. Eq. (13a) is based on the assumption that the heat transfer through the flexible soft seals is negligible when compared to the total heat transferred through the insulating assembly.

The solution of Eqs. (13a) and (13b) can be used to produce pertinent engineering correlations. For example, percentage difference between the heat flux including thermal expansion effects and the heat flux at reference condition, q_{ref} , where thermal expansion is ignored is correlated to T_1 , T_e , T_o , k_1 and ΔT_o . The obtained family of correlations has the following functional form:

$$\begin{aligned} & \frac{(q_{ref} - q)}{q_{ref}} \times 100\% \\ &= [a - b(T_o) - c(\Delta T_o) - d(k_1) + e(T_e T_o \Delta T_o k_1)] \\ & \times (T_1 - T_o)^m \left(\frac{T_e}{270} \right)^n \end{aligned} \tag{14}$$

Table 3
Coefficients of correlation 14 for different h_{o1}

h_{o1} (m)	Coefficients	R^2
0.004	$a = 0.559, b = 1.08 \times 10^{-3}, c = 5.14 \times 10^{-4}, d = 11.572,$ $e = 2.74 \times 10^{-7}, m = 0.850, n = 0.1789$	0.980
0.006	$a = 0.591, b = 1.17 \times 10^{-3}, c = 5.26 \times 10^{-4}, d = 11.399,$ $e = 2.71 \times 10^{-7}, m = 0.847, n = 1.880$	0.983
0.008	$a = 0.610, b = 1.23 \times 10^{-3}, c = 5.32 \times 10^{-4}, d = 11.295,$ $e = 2.69 \times 10^{-7}, m = 0.845, n = 1.934$	0.984

where a, b, c, d, e, m, n and the correlation coefficient R^2 are listed in Table 3 for different values of h_{o1} . This correlation is obtained over the following range of parameter variations: $310 < T_1 < 400$ K, $270 < T_o < 290$ K, $50 < \Delta T_o < 150$ K, $270 < T_c < 300$ K, $0.001 < k_1 < 0.017$ W/m K, $h_{o2} = h_{o1}$, $\sum_{i=1}^2 \frac{(h_{ms})_i}{(k_{ms})_i} = 0.2$ m² K/W, and $k_2 = 0.028$ W/m K.

3. Suggested insulating assemblies with maximum enhanced insulating properties

Fig. 9(a) shows a more advanced insulating assembly. It contains an array of main and secondary gas layers supported by flexible soft seals. The secondary gas layers are vented to the atmosphere in order to provide maximum volumetric thermal expansion of main gas layers. Accordingly, the insulating properties are enhanced for the assembly provided that the main

gas possesses relatively lower thermal conductivity than the secondary gas which is the air. The insulating assembly of Fig. 9(a) provides an additional enhancement for the insulating properties which relies on the fact that the frame of the insulating assembly is supported by a flexible soft seal. This allows for an additional volumetric thermal expansion for the main gases. Moreover, insulating properties can also be enhanced efficiently by utilizing soft elastic balloons having minimized stiffness and containing gases with minimized thermal conductivities within the secondary gas layer. These balloons need to be placed in a vented layer as shown in Fig. 9(b, c). It should be mentioned that in this arrangement the main gas layer is eliminated. This assembly is suited for lower heat flux applications. Finally, it is worth noting that the degree of enhancements in the insulating properties is governed by the temperature levels that the soft seals can sustain before they melt.

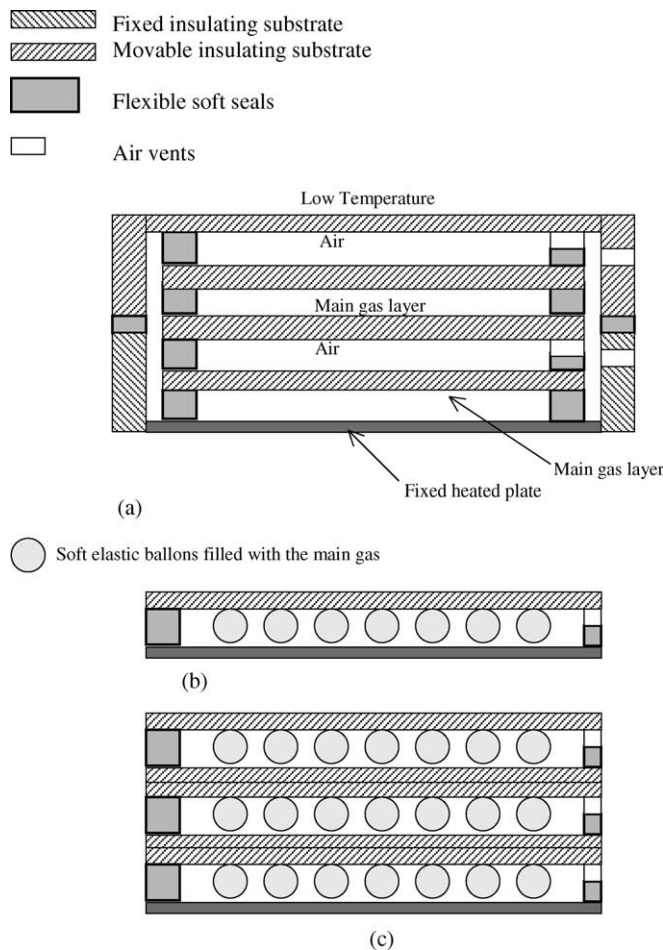


Fig. 9. Advanced assemblies with enhanced insulating properties.

4. Conclusion

A thermal insulator comprising of insulating substrates and two separated gas layers was analyzed dynamically, thermodynamically and thermally in order to investigate the enhancement in its insulating properties with respect to a temperature increase. A certain family of gases should be used to this end as other gases result in a deterioration of insulative properties at higher temperatures. Accordingly, better control in the insulating properties of thermal insulators is established by utilizing the principle of volumetric thermal expansion of gases. Moreover, more advanced insulating assemblies with maximized insulating properties are proposed. The ordinary homogeneous soft seals of these assemblies can be replaced with closed-cell foams composed of mainly small air voids separated by sealed partitions that can sustain high temperature. Accordingly, the performance of these assemblies can be improved to sustain high temperatures.

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