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Abstract

The authors put forward a new type of regenerative gas refrigerator, based on theoretical and experimental research work. The practical prototype is shown in the photograph. This paper mainly analyzes working principle, carries on theoretical calculation and analyzes the function of refrigerator by numerical method and calculation of computer. The simplified structure and working cycle of refrigerator can be seen in figure (1) and (2). The main advantages include: This new mechanism makes structure of refrigerator simpler. Compared with Solvay refrigerator, some supplementary installations can be left out and structure of middle fluctuating cylinder is simplified in this refrigerator. The whole construction of refrigerator is more compact. In addition, a part of compressive work in middle fluctuating cylinder can be transformed into motive work (but there is no use of energy in Solvay refrigerator). Moreover, the working efficiency is improved, because refrigerating capacity can be conveyed out by two sides of cylinder. The vibration and shock is weak, for its symmetrical structure. We can select proper parameters of working and structure, such as width of inlet and outlet of free piston and size of small hole on plate in the middle of cylinder, in order to adjust phase angle of various working curves and make working of refrigerator better ; but in other type of refrigerator, it is generally to change phase angle by other methods such as adjust tension of elastic ring.

The working principle of refrigerator can be analyzed with reference of figure (1). There are two compressive cylinders Vc (Vc') and two expansive cylinders Ve (Ve') which are symmetrically arranged in refrigerator. There are also two same free pistons F (F') and one fixed plate G on which a small hole is drilled in cylinder. Vmc (Vmc') is middle fluctuating cylinder. We now only analyze Ve due to symmetry of refrigerator. The initial condition of refrigerator is shown in figure (1). THe mixed pressure in Vmc is Pwa. When F begins to move upward in Vc, gas in Vmc is assumed not to flow into Vmc' through small hole. Because the left pressure of F is higher than right pressure of F (Pmc=Pwa>Pe), F does not move. Soon, Pe increased with H moving up. When Pe>Pmc, F begins to move toward the left. Pe reaches to Ph and Ve increased from zero to V2 with H continuously moving up (course 1--2). Then, gas in Vmc flows into Vmc'. In this period, the pressure on the right and left of F is same and F moves to the left with no change in speed. When angle of crank nears 180^{o}, Ve increases From V2 to V3 (course 2--3). In the earlier time that H moves down in Vc, F does not move, because gas in Vmc' is assumed not to flow into Vmc. Pe reduces from P3 to P4 (course 3--4). With H continuously moving down in Vc, gas in Vmc' flows into Vmc through small hole and F moves to the right point of expansive cylinder in same speed (course 4--1). So far, a whole working cycle of refrigerator is finished.

The experimental results of this prototype show: Under condition of no protected layer of heat insulation, practical temperature of refrigeration is -40^{o}C and refrigerating capacity is 23w (working gas in nitrogen gas of 10 kg/cm^{2} and turning speed of crank is about 120 r/min). The curve of temperature and time is

s'écoule alors dans Vmc'. A ce moment, la pression à droite et à gauche de F est la même et F se déplace vers la gauche sans variation de la Vitesse. Lorsque l'angle du vilebrequin est voisin de 180°, Ve augmente de V2 à V3 (évolution 2-3). Au début de cette phase, où H descend dans Vc, F ne bouge pas parce que le gaz dans Vmc' est supposé ne pas s'écouler dans Vmc. Pe diminue de P3 à P4 (évolution 3--4). Quand H descend continuellement dans Vc, le gaz dans Vmc' s'écoule dans Vmc par la petite perforation et F se déplace vers la droite du cylindre de détente à la même vitesse (évolution 4--1). Un cycle de fonctionnement complet du réfrigérateur est alors achevé.

Les résultats expérimentaux de ce prototype montrent que sans isolation thermique, la température pratique de refroidissement est de -40°C et que la puissance frigorifique est de 23 W (le gaz actif est de l'azote à 10 kg/cm2 et la vitesse de rotation du vilebrequin est d'environ 120 t/min). La courbe température-temps est indiquée à la fig (3). Les résultats montrent que ce réfrigérateur à régénération est possible du point de vue théorique et réalisable en pratique.

Le calcul théorique montre que ce réfrigérateur fonctionne normalement et que son effet frigorifique est de 16,5 %. On peut aussi obtenir la loi de variation des paramètres fonctionnels par une méthode numérique utilisant un ordinateur. La loi suivant laquelle P/Pmax varie est indiquée fig. (4). Les cartes d'indicateur du cylindre de détente et de l'ensemble de la machine sont présentées fig. (5). La loi de répartition de la masse de Me dans le cylindre de détente, de Mc dans le cylindre de compression et de MK dans l'espace mort peut être observée fig. (6). A partir de ces figures on peut voir que le réfrigérateur à régénération fonctionne normalement, parce que l'aire du diagramme de fonctionnement en cycle fermé du cylindre de détente est grande.

Bien que la température de refroidissement ne soit pas très basse et que la puissance frigorifique ne soit pas très grande en raison des diverses pertes, on peut améliorer le fonctionnement de ce réfrigérateur à régénération en optimisant certains paramètres de la structure et en construisant un meilleur prototype.

shown in figure (3). The results show that this regenerative refrigerator is feasible in working principle and practical use.

Theoretical calculation shows that this refrigerator works normally and its coefficient of refrigeration is 16.5%. We can also get the variational law of functional parameters by numerical method and calculation of computer. THe law the P/Pmax variates along with is shown in figure (4). The indicator cards of expansive cylinder and total machine are shown in figure (5). The distributive law of mass such as Me in expansive cylinder, Mc in compressive cylinder and Mk in clearance volume can be seen from figure (6). From these figures, we can see that this regenerative refrigerator works normally, because enclosed area of working curve of expansive cylinder is great.

Although the temperature of refrigeration is not very low and refrigerating capacity is also not great because of various losses in this prototype, we can improve working function of this regenerative refrigerator by optimizing some parameters of structure and making construction of prototype better.

UN NOUVEAU TYPE DE REFRIGERATEUR A GAZ ET REGENERATION.

RESUME : Les auteurs présentent un nouveau type de réfrigérateur à gaz et régénération en s'appuyant sur des travaux de recherche théoriques et expérimentaux. Le prototype est présenté dans une photographie. Ce rapport analyse surtout le principe de fonctionnement, expose le calcul théorique et examine la fonction du réfrigérateur par une méthode numérique de calcul par ordinateur. La structure simplifiée et le cycle de fonctionnement du réfrigérateur peuvent être observés fig (1) et (2). Les principaux avantages sont les suivants : le nouveau mécanisme simplifie la structure du réfrigérateur. En comparaison du réfrigérateur Solvay, certains équipements auxiliaires peuvent être abandonnés et la structure du cylindre fluctuant du milieu est simplifiée. L'ensemble de la construction du réfrigérateur est moins encombrant. De plus, une partie du travail de compression du cylindre fluctuant du milieu peut être transformée en travail (mais l'énergie ne sert à rien dans le réfrigérateur Solvay). En outre, le rendement du fonctionnement est amélioré, parce que la puissance frigorifique peut être acheminée à l'extérieur par deux côtés du cylindre. Les vibrations et les chocs sont faibles en raison de la structure symétrique. On peut choisir des parametres appropriés de fonctionnement et de structure, tels que la longueur d'entrée et de sortie du piston libre et les dimensions d'une petite perforation sur la plaque au milieu du cylindre, de façon à ajuster l'angle de phase de diverses courbes de fonctionnement et à améliorer le fonctionnement du réfrigérateur ; dans un autre type de réfrigérateur il s'agit généralement, pour modifier l'angle de phase, d'autres méthodes telles que le réglage de la tension de l'anneau élastique.

Le principe de fonctionnement du réfrigérateur peut être analysé en se référant à la fig (1). Il y a deux cylindres de compresseurs Vc (Vc') et deux cylindres de détente Ve (Ve') disposés symétriquement dans le réfrigérateur. Il y a aussi deux pistons libres identiques F (F') et une plaque fixe G sur laquelle est ménagée une petite perforation dans le cylindre. Vmc (Vmc') est le cylindre oscillant du milieu. Les auteurs n'analysent maintenant que Ve, le réfrigérateur étant symétrique. L'état initial du réfrigérateur est présenté fig (1). La pression mixte dans Vmc est de Pwa. Lorsque F commence à monter dans Vc, le gaz dans Vmc est supposé ne pas s'écouler dans Vmc' par la petite perforation. La pression de gauche de F étant supérieure à la pression de droite (Pmc = Pwa > Pe), F ne se déplace pas. Puis Pe augmente avec la montée de H. Lorsque Pe>Pmc, F commence à se déplacer vers la gauche. Pe atteint Ph et Ve passe de 0 à V2, H montant de façon continue (évolution 1--2). Le gaz de Vmc

A NEW TYPE OF REGENERATIVE GAS REFRIGERATOR

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Introduction

As is known to all, the application of cryogenic refrigerator is now widespread day by day and research work concerned is always carried on. Small sized, simple and reliable cryogenic refrigerators which are used for cold resource have been eagerly required in many fields.

The authors put forward a new type of regenerative gas refrigerator, based on theoretical and experimental research work. The practical prototype is shown in photograph. This paper mainly analyses working principle, carries on theoretical calculation and analyses the function of refrigerator by numerical method and calculation of computer. The simplified structure and working cycle of refrigerator can be seen in figure (1) and (2). The main advantages include: This new mechanism makes structure of refrigerator simpler. Compared with Solvay refrigerator, some supplementary installations can be left out and structure of middle fluctuating cylinder Vmc (V'mc) is simplified in this refrigerator. The whole construction of refrigerator is more compact. In addition. a part of compressive work in middle fluctuating cylinder can be transformed into motive work (But there is no use of energy in Solvay refrigerator, for total compressive work in middle fluctuating cylinder can only be changed to heat which is discharged to the air.) Moreover, the working efficiency is improved, because refrigerating capacity can be conveyed out by two sides of cylinder. The vibration and shock is weak, for its symmetrical structure. We can select proper parameters of working and structure, such as width of inlet and outlet of free piston and size of small hole on pleate in the middle of cylinder, in order to adjust phase angle of various working curves and make working of refrigerator better (But in other type of refrigerator. it is generally to change phase angle by other methods such as adjust tension of elastic ring. So, frictional loss of ring is existed.)

Analysis of working principle

The working principle of refrigerator can be analysed with reference of figure (1). There are two compressive cylinders Vc (Vc') and two expansive cylinders Vc (Vc') which are symmetrically arranged in refrigerator. There are also two same free pistons F(F') and one fixed plate G on which a small hole is drilled in cylinder. Vmc(Vmc') is middle fluctuating cylinder. We now only analyse Ve due to symmetry of refrigerator. The initial condition of refrigerator is shown in figure (1). The refrigerator is assumed to reach steady working condition in initial stage of working cycle, and piston H is at the lowest point in compressive cylinder and free piston F is at the right point of expansive cylinder. Due to a part of high pressure gas (P=Ph) enters right volume of middle plate (namely Vmc) through small hole in the end period of last working cycle, gas of low pressure Pl in Vmc is mixed with gas of high pressure. The mixed pressure in Vmc is Pwa. When F begin to move upward in Vc, gas in Vmc is assumed not to flow into Vmc' through small hole. Because the left pressure of F is higher than right pressure of F(Pmc=Pwa>Pe), F does not move. Soon, Pe increases with H moving up. When Pe>Pme, F begin to move toward the left. Pe reaches to Ph and Ve increases from zero to V2 with H continuously moving up(course 1--2 in figure(2)). Then, gas in Vmc flows into Vmc'. In this period, the pressure on the right and left of F is same and F moves to the left with no change in speed. When angle of crank α nears 180°, Ve increases from V2 to V3(course 2--3). In the earlier time that H moves down in Vc, F does not move, because gas in Vmc' is assumed not to flow into Vmc. Pe reduces from P3 to P4(course 3--4). With H continuously moving down in Vc, gas in Vmc' flows into Vmc through small hole and F moves to the right point of expansive cylinder in same speed (course 4--1). So far, a whole working cycle of refrigerator is finished.

Experimental result

The experimental results of this prototype show: We use sponge as protected layer of heat insulation. practical tempreture of refrigeration is -80°c and refrigerating capacity is 33w (working gas is nitrogen gas of 10 kg/cm^2 and turning speed of crank is about 120 r/ min). The curve of tempreture and time is shown in figure (3). The results show that this regenerative refrigerator is feasible in working principle and practical use. We can also get the variational law of functional parameters by experiment and calculation of computer. The law that P/Pmax variates along with α is shown in figure (4). The indicator cards of expansive cylinder and total machine are shown in figure(5). The distributive law of mass such as Me in expansive cylinder, Mc in compressive cylinder and Mk in clearance volume can be seen from figure(6). From these figures. we can see that this regenerative refrigerator works normally, because the variational law of pressure and mass is ideal and enclosed area of working curve of expansive cylinder is great.

Analysis of numerical method

We can also get the variational law of functional parameters by numerical method, on the basis of mechanical analysis of free piston, with reference of figure(1).

Because compressive piston H moves in sine law, we can get:

$Vc(\alpha)=(1/2)F\cdot Veo(1+COS\alpha)$

Veo---maximum of Ve, F---Vmax/Veo. α --- angle of crank

Suppose Vk as clearance volume, we can have:

$V=Vk+Ve+Vc$

$P=P\Sigma Mi/((Vk/Tk)+(Ve/Tk)+(Ve/Te)+(Vc/Tc))$ ----(1)

When compressive piston H moves up to some angle B,

$(Pe-Pmc)S=Ff$

Pe---pressure of Ve Pmc---pressure of Vmc

Ff---frictional force between free piston and cylinder.

Suppose: H=Tc/Tk, L=Vk/Veo, Q=Tc/Te.

We can get:

$P(B)=R\Sigma Mi/((Vk/Tk)+0+(Vc(B)/Tc))$ ------(2)

Combine (1) with (2), we can obtain:

$P=P(B)\cdot(LH+(Vc(B)/Veo))/(LH+(Ve/Veo)Q+(Vc/Veo))$ ------(3)

From formula (3), we can find the solution of law of $P=P(\alpha)$, after getting relation between Ve and α. The motional differential equation of free piston can be shown according to second law of Newton's:

$m(d^2Ye/dt^2)=(Pe-Pmc)S-Ff$ ------(4)

From (3) and (4), we can have:

$d^2(Ve(\alpha)/Veo)/d\alpha^2=P(B)\cdot(LH+Vc(B)/Veo/(mw^2Yo/S\cdot(LH+QVe(\alpha)/$

$Veo+Vc(\alpha)/Veo)-VeoS(Pl+Ph)/(2mw^2Yo)$ -----(5)

S-------area of free piston ends

Ye------moving disdance of free piston

w-------speed of turning angle of crank

m-------weight of free piston

t------time

P(B) can be calculated by following equation:

$d^2(Ve(\alpha)/d\alpha^2=0$

and Vc (B) can be computered by formula (2).

Having the aid of computer, we can calculate $Ve(\alpha)$ from formula(5) and $P(\alpha)$ from equation (3) by numerical method. On the basis of these results, we can have the variational law of functional parameters which are similar to figure(4),(5) and (6). So. the refrigerator is also proved to work normally and effectively by this numerical method.

Conclusions

On the basis of thermodynamic analysis, theoretical and numerical calculation and experimental study, feasibility of this new type of re-generative cryogenic refrigerator is verified. The distinguished features of this refrigerator include: Its structure is uncomplicated and compact. The vibration and shock is weak, for its symmetrical structure. Meanwhile, the working efficiency of this refrigerator is higher, for refrigerating capacity is conveyed by two sides of cylinder.

Although the tempreture of refrigeration is not very low and refrigerating capacity is also not great because of various losses in this prototype. we can improve working function of this regenerative refrigerator by optimizing some parameters of structure and making constrution of prototype better.

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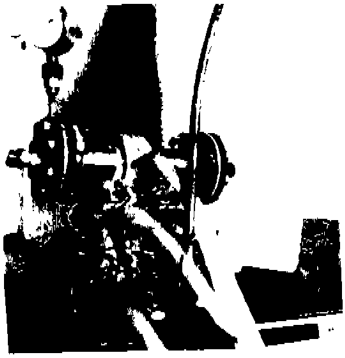

photograph

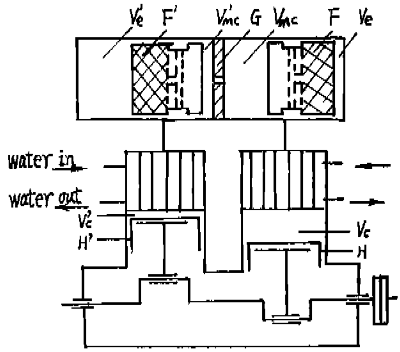

figure (1)

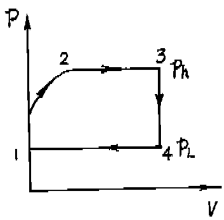

figure (2)

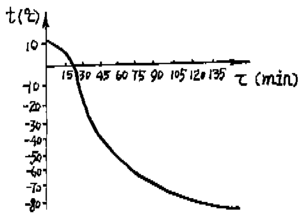

figure (3)

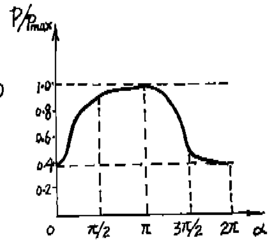

figure (4)

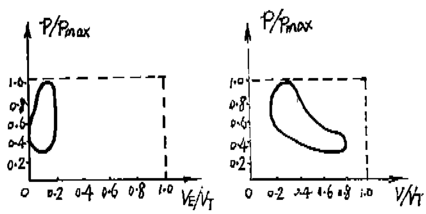

figure (5)

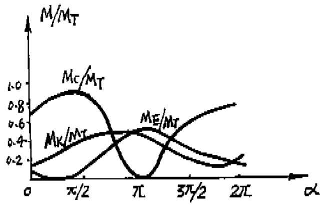

figure (6)