Compressor-fan unitary structure for air conditioning system

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Abstract. An extremely compact, therefore space saving unitary structure of short axial length is produced by radial integration of a revolving piston rotary compressor and an impeller of a centrifugal fan. The unitary structure employs single motor to run as the compressor so the airflow fan and eliminates duality of motors, related power supply and control elements. Novel revolving piston rotary compressor which provides possibility for such integration comprises the following: a suction gas delivery system which provides cooling of the motor and supplies refrigerant into the suction chamber under higher pressure (supercharged); a modified discharge system and lubricating oil supply system. Axial passages formed in the stationary crankshaft are used to supply discharge gas to a condenser, to return vaporized cooling agent from the evaporator to the suction cavity of the compressor, to pass a lubricant and to accommodate wiring supplying power to the unitary structure driver – external rotor electric motor.

1. Introduction
A heating, ventilation, and air conditioning system generally includes a closed loop refrigeration system with at least one evaporator, at least one condenser, at least one compressor and at least one airflow fan driven by an electric motor. The compressor motor and the airflow fan motor have, as usual, separate power wiring, running capacitors, start capacitors and another operation control elements. A combined rotary compressor - airflow fan unitary structure for air conditioning system has a single electric motor which drives both, the compressor and the fan. The unitary structure consists of a revolving piston rotary compressor with the stationary crankshaft and an impeller wheel (or plurality of impeller wheels) attached externally to the revolving piston compressor [1]. The mechanical structure and operating principle of the revolving piston rotary compressor with stationary crankshaft which provides possibility for such assembly are described below [2].

2. Motion analysis
2.1. Kinematics of the revolving piston compressor. A rotor block and a revolving piston of novel rotary compressor are considered, consequently, as internal cylinder (driver) and external cylinder
follower) having rolling contact at point P with transmission of the motion from the driver to the follower through the rigid link C (coupler) and a line of contact. According to the compressor structure, the vane presented in figure 1A, 1B as link C, separates suction and compression chambers and extends radially inward toward rotor block center of rotation OR through the center of the bushing mounted in the rotor block. The line connected piston center OP and point PR = e (fixed link). The line OP = f considered as a driver. The equation of motion of the compressor elements such as integral revolving piston – vane, rotor block with vane bushing can be derived by choosing the orthogonal coordinate system fixed to the stationary crankshaft with origin in the rotor block center OR, the X axis lie along common line, namely the line of centers directed to the point of contact P and the Z axis coincided with the stationary crankshaft axis. For plane triangle OPR (see figure 2A), as per the Law of Sines and the Law of Cosines

\[
e \sin \theta = f \sin \phi ; \quad d = e \cos \theta + f \cos \phi
\] (1)

Due to the fact that the revolving piston-vane is integral part and rotates as one solid body around Z-axis, there is no reciprocating movement of the vane. The flats of the bushing implanted in the rotor block slide along the suction and discharge sides of the vane with change of the turning angle \( \theta \). The part of the vane \( L(\theta) \) exposed to the suction and discharge pressure inside of the working chamber will be

\[
L(\theta) = P_P - d
\] (2)

where radius of the piston \( R_p = R_r + e \), and radius of the rotor block \( R_R = f \). After substitution and transformation, exposed length of the vane can be expressed as

\[
L(\theta) = e (1 - \cos \theta)^2 + f \{1 - (\lambda \sin \theta)^2\}^{1/2}
\] (3)

where \( \lambda = e/f \). We can use binominal series shown below for the last term of the Eq.3

\[
(a + b)^n = a^n + n a^{n-1} b + n(n-1)/2! [a^{n-2} b^2] + n(n-1)(n-2)/3! [a^{n-3} b^3] \ldots
\] (4)

with \( a = 1 \), \( b = -(\lambda \sin \theta)^2 \) and \( n = \frac{1}{2} \). After expanding the root into a binominal expansion with inclusion of the first two terms as the series rapidly converges, we obtain

\[
L(\theta) = e (1 - \cos \theta)^2 + \lambda^2/(2 \sin \theta)^2 - \lambda^3 \sin \theta / 8 + \ldots
\] (5)

Thus the length of the exposed part of the vane very approximately (error 0.15%) will be:

\[
L(\theta) = e (1 - \cos \theta + \lambda^2/(2 \sin \theta)^2)
\] (6)

The bushings inside of the rotor block cavity slides along the vane sides and turns to accommodate vane position with the change of the piston-rotor block position (see figure 1B). Differentiating Eq.(5) with respect to time and denoting \( d\theta/dt = \omega \) we obtain the sliding speed \( V_{BV} \) between the bushing and vane with change of the turning angle.
\[ V_{BV} = e \omega (\sin \theta + \frac{\lambda}{2} \sin 2\theta) \]  

(7)

where \( \omega \) is angular velocity of the rotor block.

**Figure 1.** A schematic view of the revolving piston compressor mechanism

The rotor block bushing turning angle \( \phi_1 \) (see figure.1B) with change of the vane rotational angle \( \theta \) will be

\[ \phi_1 = \arcsin \left[ e \frac{\sin \theta}{(R_R - R_B)} \right] \]  

(8)

where \( R_B \) is the radius of the roller bushing. The values of the bushing turning angle \( \phi_1 \) with change of the rotational angle \( \theta \) in the limits 0-2\( \pi \) (single revolution) are shown in figure.2.

**Figure 2.** Turning angle of the bushing with a change of the vane angular position.
2.2. Velocity. Motion of the internal cylinder is transmitted to the external cylinder through the driving link $C$. If driving link $C$ rotates counterclockwise with constant angular velocity, the follower will revolve in the same direction at a varying (accelerating and decelerating) speed. The relative velocity between the cylinders is a function of the driver angle $\theta$, radii of the contact cylinders, centers distance. The linear velocities of the piston $v_p$ and the rotor block $v_r$ are shown below:

$$V_p = \frac{dS_p}{dt} = \frac{dS_p}{d\theta} = \omega R_p$$

$$J_0^\theta v_R = \frac{dS_R}{dt} = \omega \int dx \frac{d\theta}{d\theta} = \omega d$$

where $S_p$ and $S_R$ are revolving arcs of the piston and rotor block. The relative velocity of the rotor block to the revolving piston

$$\Delta v = \omega (R_p - d)$$

Taking derivative we find that

$$\frac{dv}{dt} = \omega \left( \frac{d(d)}{dt} \right) (d\theta/dt) = \omega \left( \frac{d^2}{dt} \right) = -\omega \lambda R_R \sin \theta (1+\lambda/2 \cos \theta)$$

The extreme values of the roller relative velocity are shown below:

$$\Delta v_{max} = 2\omega (R_p - R_R) \quad \text{and} \quad \Delta v_{min} = 0$$

Effect of the $R_p/R_R$ ratio on the values of the relative velocity between the rotor block and the revolving piston at different vane angular positions is shown in figure 3. It can be seen that rather smaller ratio gives us lower relative velocity between rotating in one direction rotor and piston.

![Figure 3. Effect of the radii ratio on the relative velocity of the cylinders.](image)

3. Structure of the revolving piston rotary compressor

A construction of a compressor-fan unitary structure combines a revolving piston rotary compressor having a stationary crankshaft with an impeller wheel or plurality of wheels used in radial flow (centrifugal) fans. Developed for such unitary structure novel revolving piston rotary compressor contains (see figure 4) a rotor 1 of the driver -external rotor electric motor 2, which is integrated with concentrically situated pump rotatably assembled on the stationary crankshaft, [3]. A mounting plate 3 is rigidly fixed to the upper end of the stationary crankshafts which supports the assembled on it motor stator 4, spinning around it rotor block 5, a revolving piston 6, and an impeller wheel 61. The revolving piston is disposed eccentrically outside of the rotor block with the direct (no operating
clearance) contact between the inner peripheral surface of the revolving piston and external peripheral surface of the rotor block. The direct contact of the revolving piston inner surface with the rotor block lies in the plane passing through the lines of centers of their rotation (see figure 1, point P). In such kinematic pair (an external and internal cylinder) a motion of the rotor block (driver) will be transmitted to the revolving piston (follower), and both cylindrical parts rotate in the same direction due to a force developed at the contact line. At the point of contact P the tangential velocities of the rotor block and the revolving piston are unidirectional and equal. It means that there is no sliding friction and frictional losses at the contact line of both parts are minimal due to the relatively low value of the rolling friction. In addition, there is no high-low side leak and the angular momentum developed through such contact will be supplemental to the momentum transferred from the rotor block to the revolving piston through the coupler – vane which is rigidly fixed to the piston.

**Figure 4.** A side sectional view of a revolving piston rotary compressor-impeller wheel unitary structure.

3.1 Suction System. The suction system of the novel rotary compressor consists of an input suction cavity 6 which is disposed on the mounting plate, an electric motor compartment 7 equipped inside with an impeller (not shown) which has been rigidly fixed to the revolving rotor block head below the stator, and a variable volume suction chamber 40 (see figure 5). The motor compartment 7 is in fluid communication as with the input suction cavity through a channel 8 formed inside of the crankshaft, so with the suction chamber through a vertical channels 41 formed in the wall of rotor block 5 and a suction port 42, as shown in figure 5. A suction inlet 9 directs a vapor-liquid mixture of refrigerant and lubricating oil through a screen (to filter an impurities) into the inner volume of the input suction cavity 6, where gas flows to the top and the liquid collects behinds the separating wall 10 having metering oil
delivery hole at the bottom. The refrigerant drawn from the suction input cavity 6 will be
delivered to the part of the electric motor compartment spaced below the stator where
centrifugal force triggered by rotation of the rotor block and rigidly fixed to it impeller will
forcibly guide oil to the mitering (bleeding) hole formed in the side wall of the rotor block.
The vapor portion of the refrigerant, pressure of which has been increased by the impeller, will be
supercharged through the suction port to the suction chamber. Such arrangement of the suction system
prevents direct delivery of gas-liquid-oil mixture to the suction chamber by double separation of liquid
and vapor, increases the liquid refrigerant storage capacity and provides cooling of the compressor
motor during and after its duty cycle.

3.2 Revolving Piston - Vane Assembly. The vane 19 of the compressor separates suction chamber 40
and compression chamber 44, as shown in figures 4, 5, and has an axial edge 11 rigidly fixed without
operating clearance to the inner periphery of the revolving piston 6 with opposite axial edge 12 fitted
in between sliding segmental bushings 43 mounted in the rotor block. The vane, however, not only
serves to separate the working cavity between rotor block and revolving piston into suction chamber
and compression chamber, but it forms also a mechanical connection (coupler), between the driver
(rotor block) and follower (revolving piston) so, that the external rotor motor revolves simultaneously
the rotor block 5 and the revolving piston 6. Such coupling arrangement also prevents slippage in
between cylindrical surfaces at the line of the cylinders contact. The vane radial edges 13 are axially
rigidly fitted in between the revolving piston heads without operating clearances. It eliminates
frictional losses and also blocks high-low side leaks. Integration of the vane with the revolving piston
excludes frictional and leakage losses observed in contemporary rotary compressors where a vane and
roller slide against facing surfaces of the stationary cylinder block and stationary heads. There is also
no “grinding” interference between vane and roller (roller and spring are eliminated) and, in addition,
nose of the vane (axial edge 12 does not required any special treatment, such as precision machining,
TiN coating, special vane tip seal, etc., recommended and used in prior art rotary compressors.

3.3. Discharge System. Referring now to figures 4, 5 and 6, the discharge system of the compressor
comprises a discharge valve system arranged in the vane 10, a horizontal passage 14 formed in the
revolving piston head 15, cone-shaped gas expansion cavity 16 which is in fluid communication with
the discharge line 18 through a discharge gas exhaust channel 17 formed axially in the crankshaft.

Figure 5. A partial horizontal cross-sectional view of the revolving piston rotary compressor.
The vane consists of a discharge side plate 20 (see figure 6) and suction side plate 21 which are held together (by welding, riveting, plurality of screws, etc.), and a discharge valve cavity 22. At least one reed type valve 23 is clamped to the back of the discharge side plate against discharge port opening 24 facing compression chamber 44. The suction side plate 21 is formed with a valve stop which prevents excessive movement of the reed valve. The discharge valve cavity 22 is in fluid communication with the horizontal passage 14 through longitudinal channel 19 formed in the wall of the revolving piston.

3.4 Lubrication

The oil accumulation and distribution passageways (see figures 4, 5, 7) comprise an oil pump 45 having an oil input cavity 46, an oil discharge cavity 47, a cone shaped oil retaining reservoir 48 spaced above the electric motor compartment, plurality of vertical channels 70 formed in the wall of rotor block. The oil pump discharge side is in fluid communication with formed in the stationary crankshaft and axially extending channels through which oil delivered to plurality of oil passages to lubricate the compressor bearings 53, and a channel 56 which supplies oil to the reservoir. The rotor block vertical channels 70 are in fluid communication as with the reservoir so with the input side of the oil pump through the orifices 54.

During operation of the compressor the liquid/gas inlet mixture is forced under pumping pressure into the reservoir 48 are thrown against the wall of the reservoir by action of centrifugal force. This cause a boundary layer to be formed between the oil and relatively lighter gas in axial region of turbulence chamber (reservoir). The layer in most instances takes shape of the funnel which in longitudinal section.
approximates a cone-shape or parabolic form. Figure 7 depicts a fluid contained in the reservoir that rotates with a constant angular velocity $\omega$ about the vertical Z axis. The gravity vector acts in the negative Z direction. For steady-state rotation, the fluid rotates with the reservoir as a rigid body. The fluid volume underneath the paraboloid of revolution is the original fluid volume and the shape of the paraboloid of revolution depends only upon the angular velocity $\omega$. The volume of the vapor separated from oil

$$v = \int_0^h \frac{R_0^2 - x^2}{h} dx - \pi h R_{cs}^2 = \pi h \frac{R_0^2 - R_{cs}^2}{2}$$

where

$$h = \frac{\omega^2 R_0^2}{2g}$$

Here $h$ is the depth on the axis Z, $R_0$ is the radius of the rotor block, $R_{cs}$ is the radius of the crankshaft, $g$ is the acceleration of gravity. The reservoir has an axial outlet 17 formed at the top portion of the stationary crankshaft for discharge of the vapor collected above the paraboloid surface and plurality of oil outlets 54 connected to plurality of vertical channels 70 through which oil flows downwardly under gravity into an intake cavity of the oil pump. The reservoir has cone-like shape which diverges outwardly from the lower portion to a circular lip and spinning coaxially with the rotor block. By providing such structure, the whirling oil-vapor mixture formed in such turbulence chamber is prevented from uncontrollable movement and possible extension of the vertex toward the bottom of the reservoir. During operation of the compressor the lubricant delivered into the reservoir 48 through an axial slot 56 is thrown outward by centrifugal force and forms also an annular seal of liquid at the periphery of chamber and along the axial edge 12 of the vane. Any leakage that may take place past the sides of the vane or past the ends 13 of the rotor block facing piston heads will be leakage of the lubricant inward into the crescent-shaped space, as this lubricant is under the delivery pressure (discharge + pumping) in addition to the pressure due to centrifugal force.

4. Arrangement of the compressor-fan structure in an air conditioning system

Figure 8 illustrates the operation of some typical cooling units equipped with the compressor-fan unitary structure, where figure 8A shows the airflow in a window / wall mounted unit and figure 8B shows the air circulation in a condensing unit.

Referring now to the figure 8, it will be seen that a combined revolving piston compressor-fan unitary structure is compact and integrates an electric motor, rotor block, revolving piston, and an impeller wheel of a centrifugal fan on short axial length of a stationary crankshaft. Disposed around and extending axially along the compressor-fan structure is a scroll shaped housing, which is fixed to the frame of an air conditioning unit (not shown) and which performs also as a safety screen surrounding a spinning assembly. The construction of the revolving piston rotary compressor makes it possible to attach an impeller wheel (or plurality of wheels) externally to the extended flange of upper or lower piston head or fix it to the circumference of the revolving piston. A magnetic clutch controlled by a thermostat can be utilized to engage or disengage of the impeller wheel. The compressor-fan structure employs single driver-external rotor electric motor, which comprises a rotor installed outside of the stator. Such motors have much higher torque, wider speed range, higher operating efficiency even at low rotational speed, outstanding power density, low starting current, excellent dynamic characteristics, more compact design, reduced noise, vibration and lower fabrication and assembly cost than comparable internal rotor electric motors. A suction gas cools the stator spaced inside of the motor compartment of the revolving piston rotary compressor which additionally cooled also externally during operation by an air flowing through an annular space between the compressor exterior and the impeller wheel. The driver-external rotor motor of the formed unitary structure can run at 3000, 1500, 1000, 750 min$^{-1}$ (50Hz) and is suitable for operation on frequency converters with all-pole sinusoidal filters.
The revolving piston rotary compressor-fan unitary structure eliminates duality of motors, related electrical power transmission and control elements.

**Figure 8.** A schematic vertical cross section of wall / window (A) and air-cooled condensing unit (B) utilizing compressor-fan unitary structure

Use of the unitary structure in the unit with radial flow belt-driven fan may exclude also such mechanical parts as belts, motor and fan pulley, belts tension adjusters, etc., and improve their performance.

The stationary crankshaft supporting the unitary structure is mounted centrally and has only one extension projecting outwardly from upper part of the structure with refrigerant inlets/outlets and power input spaced at the top of the stationary crankshaft. Such a design item made it possible to form storage space above the mounting plate and locate in this space suction and liquid line connection couplings, service valves, and a terminal box which may housing an electrical terminal, start and run capacitors, a solid state relay, a thermally triggered overload protector, etc.. It simplifies assembly, service and inspection of an air conditioning unit. The unitary structure can be readily removed for exchange, repair, when it requires servicing. Due to symmetrical design of all parts, rotating around their centers of gravity (stationary crankshaft with rigidly fixed to it stator), only a relative rotation around different centers will happen and therefore no counterweight and practically no balancing is needed and if any imbalance is found it may be removed externally.
Conclusions.

1. A compressor-fan unitary structure is composed of a revolving piston rotary compressor with a fan. The unitary compressor-fan structure utilizes a single external rotor electric motor to drive compressor and cooling fan used in an air conditioning system.

2. Design of novel revolving piston rotary compressor which provides possibility for such structure comprises a stator of the external rotor motor fixed on the stationary crankshaft, rotor block concentrically spaced to the stator and driving a piston which is surrounded and eccentrically set to the rotor block. The piston is equipped with a rigidly fixed a vane- discharge valve module spaced inside of the piston cavity and bolting lugs spaced externally.

3. There are no operating axial clearances between the vane module and the piston heads, and radial operating clearances between the unidirectional spinning rotor block and the revolving piston. The frictional and leakage losses between the radial ends surfaces of the rotor block and facing surfaces of the piston heads will be minimal because of relatively low rubbing speed between synchronously revolving in one direction components and formation of high pressure oil seal film formed along the contacts due to a centrifugation.

4. A suction side delivery scheme has two-stage process of liquid-vapor separation: first- in the input cavity due to gravity and second-in the motor compartment due to a centrifugation. The vapor is supercharged in the suction chamber and simultaneously cools motor. A direct delivery of a suction gas to the suction chamber is eliminated. The compressor cooled also by an air movement triggered by the fan which is fixed externally to the pistons bolting lugs.

5. The unitary structure is arranged on a stationary crankshaft of short axial length and rotates around the center of gravity. The forces triggered by spinning of the unitary structure are symmetrically load bearings spaced below and above the stator which is fixed to the stationary crankshaft.

6. An extremely compact, therefore space saving unitary structure provides a cooling air movement and operation of the compression cycle by utilizing single driver-external rotor electric motor. It reduces, cost, assembly and service time of the air conditioning system due to lower number of components (single motor and one set of control elements) and related wiring procedures.

References.

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