Approach To The Numeric Geometry Analysis of Positive Displacement Compressors, Its Application To A Single Screw Compressor Simulation And Verification By Experiment

Kirill Michailovich Ignatiev
Kirill.Ignatiev@Emerson.com

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Kirill IGNATIEV

Emerson Climate Technologies, Inc.
Sidney, OH, USA
E-mail: Kirill.Ignatiev@Emerson.com; Phone: +1 937 498 3844

ABSTRACT

Thermodynamic models to simulate positive displacement compressors are well known for a few decades already and can describe the compressor performance quite well. One of the most complex part of the simulation process however is the positive displacement compressor geometry simulation. In the current context, under geometry simulation, values of working compressor volumes, as well as cross-sections of port openings, at different shaft (rotor) angles are considered.

In the current paper, as an example, the Greene formula approach was applied to a geometry simulation of a single screw compressor. Working chamber geometry was defined by "cutting " it with the gate rotor blade; flute volume was computed using Greene formula; suction and discharge ports were intersected with this volume so that port opening contours were defined and their respective cross sectional areas were calculated. The results of this geometry simulation were applied for a thermodynamic model of a single screw compressor. Experimental investigation of a single screw working process using pressure transducers has been conducted. Geometry simulation data was applied to calculate compression work from experimental pressure traces.

Pressure-volume diagrams obtained experimentally were compared to the simulated ones. Also, indicator work obtained from simulation and experiment, was compared to the power input to the shaft, and demonstrated good correlation.

1. INTRODUCTION

Traditionally, volume and area computations are done either by utilizing close form analytical formulation, or by numerical area integration. A very good illustration in respect to Single Screw compressor was demonstrated by Bein, Hamilton (1982), Herai *et all* (1986) and Sun *et all* (2010) A very good illustration of the same approach fin case of scroll compressor geometry is provided by Bell *et all* (2010). In all of these approaches the areas are divided into zones with of simpler geometry, areas of these zones are computed by numerical integration and added together. Interestingly, in the vast majority of positive displacement compressors, working volume and porting is achieved by a relative motion of solid parts. From this perspective, it is beneficial to calculate volumes and cross- sectional areas of ports from the mathematical description of these solid body surfaces. The most flexible way is to represent the analyzed surfaces numerically as a polygon as an array of node coordinates. This approach allows for simulation analysis structure to be split into 3 steps:

1. From the generic compressor parameters, describing a specific compressor type (in the current example, a single screw compressor), generate numeric description of surfaces as polygons;
2. Based on this description, calculate volumes and porting cross- sectional areas numerically using the Green formula (numeric geometry analysis) .
3. Apply the numeric geometry analysis results for thermodynamic working process simulation.

Step 1 of this process is compressor-dependent. Step 2, though it is also somewhat compressor dependent, contains the vast majority of procedures which are independent of the compressor type. Step 3 can be common for all compressor types. The data interaction between geometry simulation and compression process simulation is achieved through a data exchange in a tabular form, where chamber volumes, volume changes, and porting cross-sectional areas are tabulated as a function of compressor shaft rotation. The same tabular form, as it would be shown

below, can be used for experimental pressure trace evaluation. Therefore, the purpose of the geometry analysis is to generate this table, based on specific parameters of the compressor.
Experimental Pressure trace analysis for a Single Screw compressor has been previously conducted by Herai *et all* (1986).

2. GEOMETRY ANALYSIS

1.1.Geometry Analysis: Greene Formula

The main idea of the geometry simulation is the following: Since the compression volumes, as well as porting cross-sectional areas are formed by intermeshing solid surfaces, it makes sense to derive those volumes and areas from the description of those solid surfaces.
The mathematical formulation, which can be applied in this case, is the very well-known Green formula:

$$\iint_S \left(\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y}\right) dxdy = \oint_L Pdx + Qdy \qquad (1)$$
$$P = 0, Q = x : S = \iint_S dxdy = \oint_L xdy$$

In a finite difference form:

$$S = \sum_{j=1}^{N-1} \frac{X_{j+1} + X_j}{2} (Y_{j+1} - Y_{oj}) \qquad (2)$$

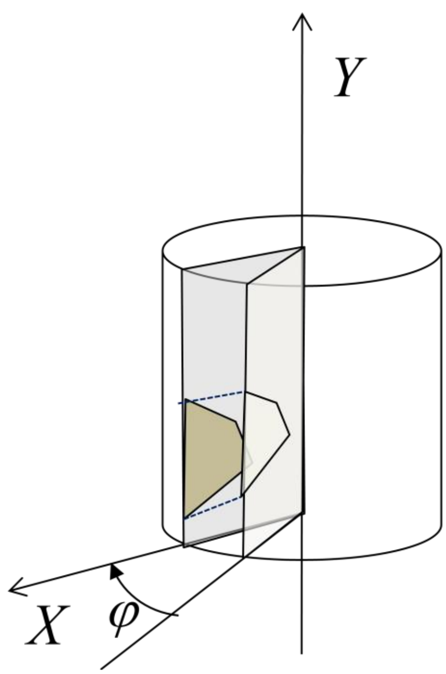

Figure.1. Volume element illustration in a cylindrical coordinate system

For a volume computation in case of cylindrical coordinate system (Fig.1):

$$V = 2\pi \iint_S Xdxdy \ ; Q = \frac{x^2}{2}; P = 0 \ ; V = 2\pi \oint_l \frac{x^2}{2} dy \qquad (3)$$

For non-axisymmetrical Volume computation:

$$V = \int_{\varphi_1}^{\varphi_2} d\varphi \oint_l \frac{x^2}{2} dy \qquad (4)$$

In Final Difference form:

$$V = \sum_{J=1}^{M} \Delta\varphi \left[\sum_{i=1}^{N} \frac{X_i^2 + X_i X_{i-1} + X_{i-1}^2}{6} \left(Y_i - Y_{i-1} \right) \right]_J \qquad (5)$$

The equations above demonstrate, that if we have a mathematical description of an intersection contour (coordinates of nodes), then the appropriate area or volume can be calculated. It is interesting to note, that if the contour represents a polygon, then the formulations (2) and (5) give the precise answer. That allows for significant reduction of number of nodes.

2.2. Multi-step geometry simulation process

If has been demonstrated, that if we can define a contour, then its area or volume can be calculated using equations (3) or (5). The following contour definition algorithm is suggested:

1. Define a geometry of one of the intersection parts
2. By applying the relative motion, 'numerically cut" the other part
3. The working volume as a contour of intersection of those two parts, is defined

In order to do it numerically, two fundamental numerical procedures were developed:

1. A procedure to define if two segments intersect or not, and if they are, define the node of intersection; Since there can be a rare occasion that a node of intersection can coincide with one of the beginning and end-nodes of the segment, each segment 'includes' one beginning node but excludes the "ending" node.

2. A procedure to define, if a node is located inside a polygon, or outside the polygon.

An illustration example of intersection of a gate rotor blade with a rotor, and the product intersection contour, is presented on Fig.2.

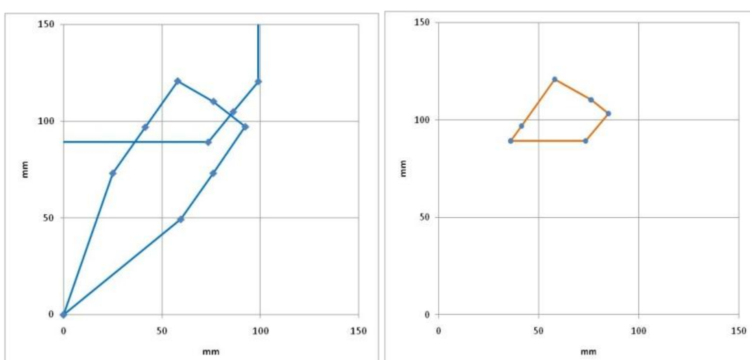

Figure 2. Intersection of gate rotor blade, rotor and their product

There is a possibility, that the intersection of two polygons can yield multiple polygons. From the numeric consistency perspective, this option was included, but the description of these multiple polygons was done by a single polygon "connecting" all those polygons together.

After the intersecting contour was defined, equation (5) was applied to calculate the volume of the working chamber of the single screw compressor (flute)

2.3. Port Opening Computations.

The same procedures were used to define port openings at different shaft angles. The outside opening of the flute was unwrapped and also presented as a contour. Different port openings were also projected on the same unwrapped surface, so the same contour intersection procedure can be applied. A specifics of the single screw compressor is that the position of both the Volume slide and Capacity slide can be independently adjusted during the compressor operation. Changing the position of the Capacity slide results in delayed communication of the flute and the suction side of the compressor, therefore the compression process is delayed and compressor capacity can be reduced. Changing the position of the Volume slide allows for adjustment of the discharge port opening and therefore independent adjustment of the built-in volume ratio of the compressor. The numeric procedure described above calculates these adjusted port openings, based on the specific value of the position of each of the slides.

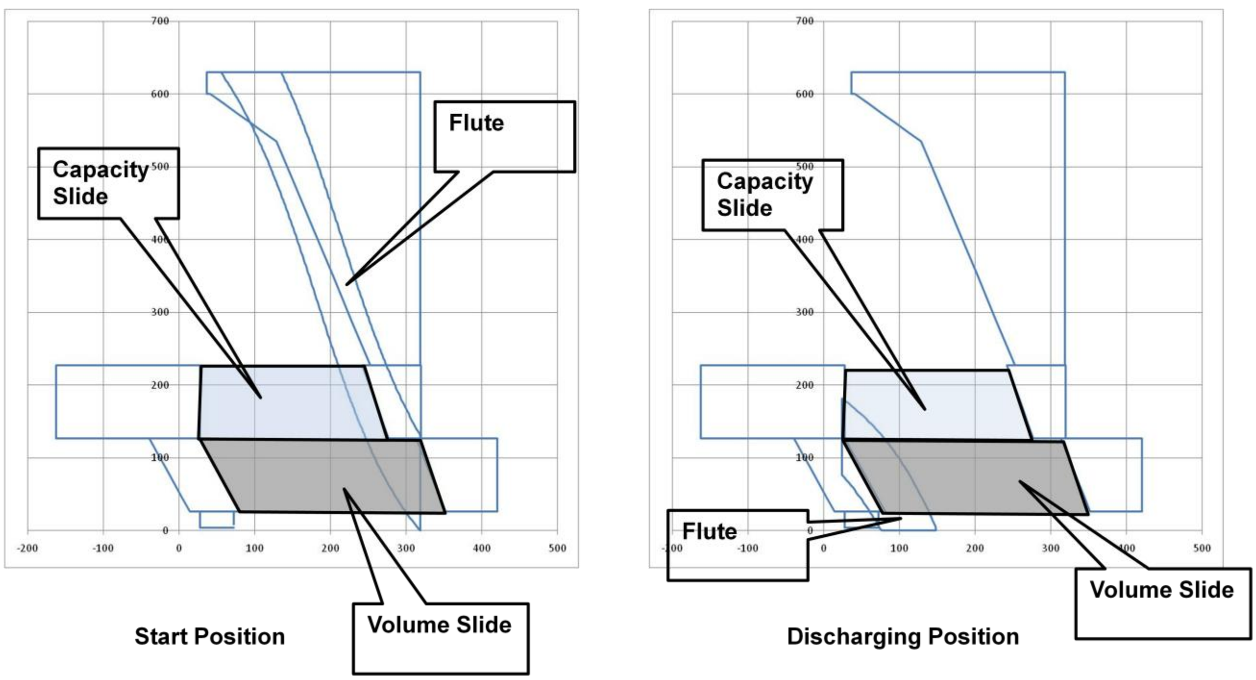

Figure 3. Flute projection with port openings at start position and discharge position

Fig. 3 illustrates flute and port interaction at different phases of the compression process: start position (beginning of gate rotor blade engagement with rotor groove), and during the discharge process.

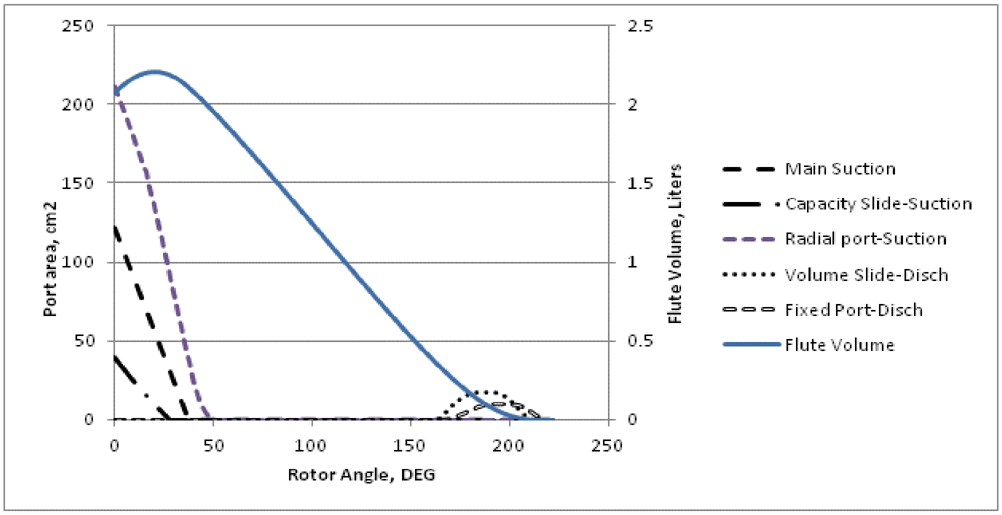

Figure 4. Graphic Interpretation of the Geometry Analysis Results

Fig.4 Illustrates graphic interpretation of the results –flute volume and port openings Vs. shaft angle. This information can then be used for compression process simulation, as well as experimental PV analysis

3. THERMODYNAMIC MODEL

As it was stated earlier, geometry analysis results were used for compression process simulation. Compression model is based on a numerical integration of a well-known and widely used set of thermodynamic equations, representing Energy, Mass and flow through an orifice equations respectively:

$$dU = PdV + \sum_{j=1}^{N_{in}} h_j dM_j - h \sum_{i=1}^{N_{OUT}} dM_i$$
$$dM = \sum_{j=1}^{N_{in}} dM_j - \sum_{i=1}^{N_{OUT}} dM_i \tag{6}$$
$$\frac{dM_i}{dt} = \eta_i S_i \sqrt{2\rho(P_{out}, T_{in})(P_{out} - P_{in})}$$

Volume and cross-sectional areas values are used from the table of the results of the geometry analysis. The values are tabulated every degree. Linear approximation is utilized for the values in between.
Refrigerant properties were accessed through DLL routines of REFPROP software package.
As the initial conditions, Suction pressure and temperature was assumed in the flute; Initial position was selected at the moment of gate rotor starting to engage the flute (“first touch”).

4. EXPERIMENTAL COMRPESSION PROCESS INVESTIGATION

Experimental compressor investigation setup included:

-Placement and installation of pressure transducers;
-Selection and Placement of synchronization devices
-Setup of pre-amplifiers and data acquisition system
-Operational conditions instrumentation;
-Post processing of the acquired data

Three different options for pressure transducer placement were considered: In the end of the rotor groove; in the tip of the gate rotor; a set of stationary transducers just above the gate rotor. Due to challenging issue of transferring a signal from moving part, the set of stationary transducers was selected, following the approach described by Herai *et all* (1986).

In a single screw compressor, compression process is quite fast one. It means that a great care should be taken in synchronizing the pressure transducer signal with the rotation of the compressor shaft. In order to do that, 2 Bently Nevada proximity probes were used. One probe was reading a signal from a pin located on the crankshaft, this giving a signal once a revolution. The other one was placed in compressor housing and was reading the rotor grooves, (providing 6 signals per revolution); angular position of these signals has been quite accurate due to known geometry of the rotor and location of the Bently probe on the compressor housing.

To acquire pressure transducer signals, data acquisition system HT600 was used. Signals were acquired at a sampling rate of 20 micro seconds(corresponding to 0.6 DEG of shaft revolution) for the duration of approximately 6 revolutions. During compressor test, when compressor operation is set at the desired condition, pressure transducer data is acquired, together with the Bently probe traces, and a time stamp, and stored as a data file.

During the post processing of the data, compressor overall performance and operating conditions, like suction and discharge pressures and temperatures, Suction mass flow, operating speed, power consumption, volume and capacity slide positions, is retrieved and synchronized with the transducer trace using the time stamp.

Capacity and volume slide positions are used to re-run the geometrical analysis for the particular positions of the slides. Compressor simulation is performed using this geometry analysis and actual operating conditions.

Pressure traces are generated using synchronizing signals from the Bently probes. Due to the nature of the pressure transducer placement, flute pressure trace is formed from the segments generated by individual pressure transducers, and the procedure for dynamic transducer calibration is applied. Flute Pressure traces are generated for consecutive 6 flutes compressing on one side of the compressor (we have transducers installed only on one side of the single screw compressor). Experimental pressure trace is compared to simulation trace.

Fig.5 illustrates a comparison between experimental and simulation flute pressures at a following condition: Tevap=-6.8C (20F), Tcond=34.5C (90F), deltaT superheat=6C, capacity slide at 100% position, volume [ratio] slide at16% position, working fluid: Ammonia. Pressure traces illustrate a very good match between simulated compression line and measured compression. Also, compression lines for consecutive flutes 1 through 6, are very close.

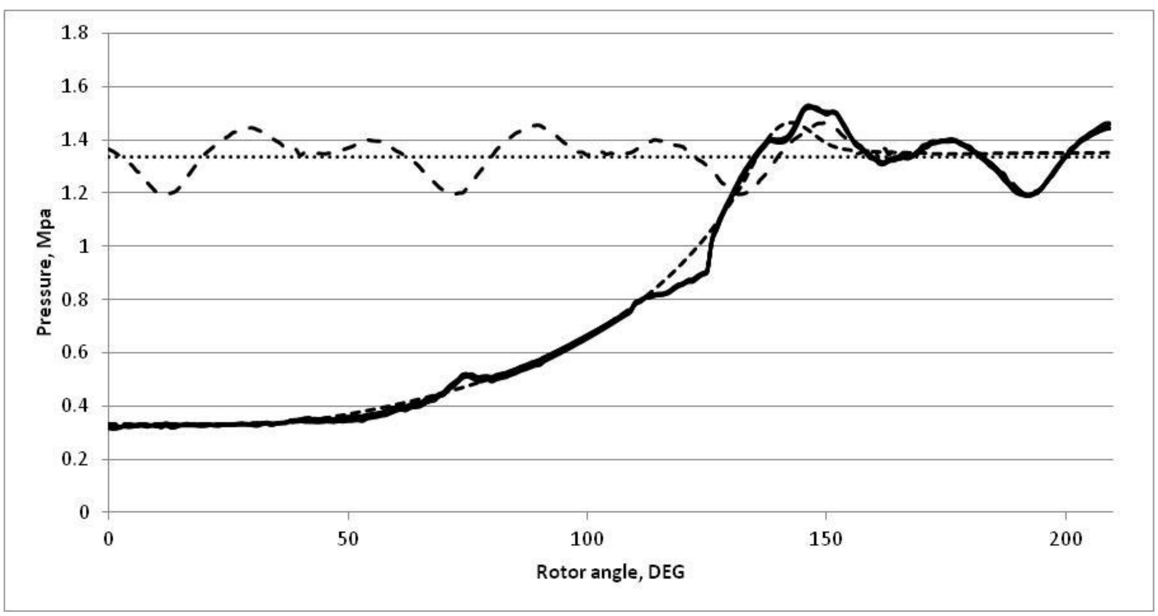

Figure 5. Experimental Vs. Simulated Pressure Trace

5. CONCLUSIONS

- Generalized numerical approach to Geometry analysis of positive displacement compressors based on Greene formula has been introduced.
- As an example, this approach has been applied to a single compressor screw geometry analysis
- Based on the geometry analysis, compression process simulation program has been developed
- Experimental analysis of the compression process in a single screw compressor has been conducted
- Geometry analysis has been also used for post processing of experimental single screw compressor pressure traces
- Pressure traces of the consecutive flutes are matching each other very well- therefore there is a very good repeatability of compression process in the consecutive flutes of a single screw compressor.
- Pressure traces obtained experimentally showed very good correlation with the pressure traces obtained by simulation

NOMENCLATURE

			subscripts
V	Volume	(m3)	
S	Area	(m2)	
l	contour	(m)	
x, X	coordinate	(m)	
y, Y	coordinate	(m)	
Δφ	angle increment	(rad)	
i, j	indexes	(-)	
U	Iinternal Energy	(kJ)	
P	Pressure	(Pa)	in, out
M	Mass of gas	(kg)	
h	Enthalpy	(kJ/kg)	
d	Differential sign	(-)	
η	Flow coefficient	(-)	
ρ	Gas Density	(kg/cub.m)	
T	Gas Temperature	(K)	in
N	Summation Number		in, out

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