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Criteria in Designing of Compressed Air Installation in Foundry Plants

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Abstract

Design of a compressed air system is a complex issue, involving the design of structures formed by the air sources, air receptors and installations connecting all structure components. Another major task is to ensure the required quality of compressed air. The paper briefly outlines the methodology of integrated and network structure design, using an objective function to find the optimal solution. In terms of quality assurance, the technological aspects of compressed air generation, treatment and distribution are defined.

1. Introduction

The performance of foundry plants largely depends on the types of installed energies used to transform the foundry plant's static structure into the dynamic –processing structure. In most foundries the energies installed include the electric, pneumatic, hydraulic energy and compressed air. Installation of various types of energies is determined by technological and economic considerations, associated not only with the structural design of receptor installations but with accessibility to the energy sources or the energy generation systems: outside the foundry plants and on the premises.

Among the three types of installed energies compressed air plays a major role, which is associated with the specificity of foundry installations and technologies and with strict requirements in design of compressed air preparation and transmission systems. The main problem is the high costs of generating and treatment of air to be used in the given receptor installation. Because of the diversity of processes and constructions involved, associated with the differences in operational characteristics of air receptors, the optimal air preparation technology, efficiency of air transmission systems and

quality of compressed air (to satisfy the constructional and operational requirements of the given installation) become the primary issues.

These issues need to be addressed already at the stage of design (or upgrading) of a foundry plant, and subsequently throughout the entire casting process, in the context of optimal energy management. The compressed air installation is designed at the stage of general planning and the process engineering. The general plan and the process diagrams determine the locations of all key structural components of the system: buildings, machines, installations, pipe systems, service lines and conveying paths.

2. Engineering objectives underlying the compressed air installation

In accordance with the general principles of the theory of systems, a foundry plant is a manufacturing system made of sub-systems and objects and involving the interrelations between them and between their properties [1]. The sets of sub-systems and their interrelations constitute structures determining the methodology of the foundry plant operation and enabling the implementation of

given processes. Structures handled by the optimisation methods are categorised into two major groups:
- integrated structures: buildings, plants, workshops, machines, installations, systems and others
- network structures: piping systems, service lines, conduits, belt conveyors.

The compressed air installation can be viewed as a classical example of an integrated and network structure within a foundry plant. The integrated structures include the compressed air sources (compressor units), receptor points (machines, installations) and buildings involved in the process. The network structure incorporates the installations connecting the components of the integrated structure. The presence of two distinct types of structures requires that the tasks involved in their arrangement be defined separately and the solutions should be sought accordingly.

Integrated structures

The main task to be handled involves the flow of materials required for technological processes between the system components. The results of such analyses are typically given in the form of a matrix wherein elements at the intersection of the row and column define the flow between a pair of objects (system components). The indicators of the flow value include: the number of passes, the mass of handled load, the product of the number of passes and the distance or the product of the path length and the load mass. To find the optimal layout of the system components, the costs of material flow between these system components have to be minimised and such tasks are handled by the operations research. One of the applicable methods involved the matrix model, the transport costs and costs of plant locations being the objective functions [1]. In this model we have n objects and n points where these could be located, the matrix K_{ij} of unit costs of load handling (PLN/(kg·m)), the matrix S_{ij} of transfers between the plants (objects) as well as the matrix L_{ij} of distances between the designed locations of system components. It is assumed that the costs of locating the objects at given points are given as C_{ij} (utilities, compressed air supply and others). The

decision variable determining that the object should be located at the given point is given as:

$$x_{ij} = \begin{cases} 1 \text{ when the object } i \text{ is stationary} \\ 0 - \text{otherwise} \end{cases} \quad (1)$$

where $i, j = 1, 2, ..., n$.

Since the distances between the objects depend on their actual locality, some additional variables need to be introduced: p, r (p, $r = 1, 2....n$) defining the locations occupied by the objects i and k. Furthermore, one object can be assigned to one location only and one location can be occupied by one object, hence the following constraints need to be satisfied:

$$\sum_{i=1}^{n} x_{ip} = 1; \quad \sum_{p=1}^{n} x_{ip} = 1. \quad (2)$$

To optimise the localisation of particular objects, the table of matrix x_{ij} is sought to minimise the following objective function:

$$\sum_{i=1}^{n}\sum_{k=1}^{n}\sum_{p=1}^{n}\sum_{r=1}^{n} k_{ij}s_{ij}l_{pr}x_{ip}x_{kr} + \sum_{i=1}^{n}\sum_{p=1}^{n} c_{ip}x_{ip} \Rightarrow min \quad (3)$$

This problem can be solved by reviewing all possible permutations (for small values of n), by the separation and constraint method or, in the case of more complex problems, by heuristic methods such as evolution algorithms.

Network structures

The typical design task involves establishing the shortest possible network connecting the objects of the integrated structure. The network connecting the plant objects (for example the compressed air installation) may have an open-loop or closed (ring-shaped) configuration. Some examples of a branched and ring-shaped network are shown in Fig. 1.
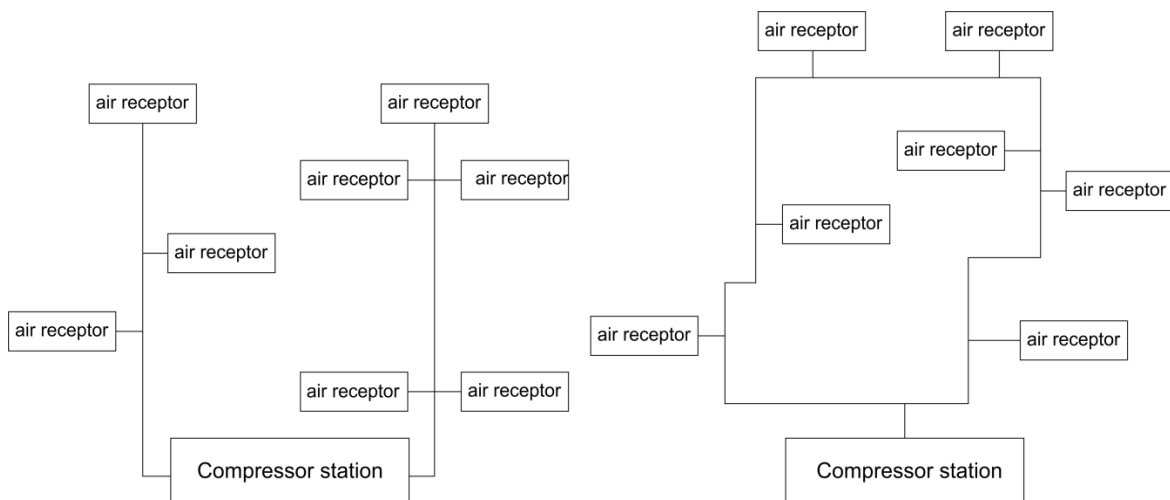

Fig. 1. Schematic diagram of a) branched, b)ring-shaped structure

The optimisation methods include:
- the separation and constraint method- to determine the minimal length of the closed-loop network connecting n points [2,5]. This method is applied to determine the shortest path of the network.

The mathematical notation of this method is given as:

$$\sum_{i,j} l_{ij} x_{ij} \Rightarrow min \qquad (4)$$

where: $i,j=1,2,...,n$, with the constraints:

$$\sum_{i=1}^{n} x_{ij} = 1; \quad \sum_{j=1}^{n} x_{ij} = 1; \quad x_{ij} = 0 \; or \; x_{ij} = 1 \qquad (5)$$

n – set of points on the plane,
i,j – pair of points within in network,
l_{ij} – length of segment connecting the pair of points.

- the method of finding the minimal length of the path between the source and the receptor point, using the Ford-Fulkesson algorithm [4]. It is applied to determine the maximal flow rate of a medium through the network or the minimal length of the connecting path. The network may encompass the supply source and several receptor points.

The mathematical model of the problem can be defined as follows:

$$\sum_{(x,y)} l(x,y) \cdot f(x,y) \Rightarrow min \qquad (6)$$

for the imposed constraints:

$$\begin{cases} 0 \leq f(x,y) \leq c(x,y) \\ f(x,N) - f(N,x) = 0 \; for \; x \neq s,t \\ f(x,N) - f(N,x) \leq b(x) for \; x = t \end{cases} \qquad (7)$$

where:
(x,y) – designation of the pipeline section connecting two neighbouring points x,y(nodes),
$l(x,y)$ – length of the section (x,y),
$c(x,y)$ – maximal throughput in the segment (x,y), determined by the pipe diameter,
$b(x)$ – demand for compressed air or water at the receptor point x,
N – set of all nodes in the neighbourhood of the node x,
$f(x,y)$ – flow rate along the pipe section (x,y) from the node x to y.

- method of analysing the installation network circuits using dynamic programming approach [4]. The method enables the practical positioning of the network structure components whilst the investments and operating costs are minimised. The input data include the parameters of the installation (pipeline): length, diameter, drag, the types of compressors (pumps) that can be installed as well as investment and operating costs to be borne depending on the compressor's type and location.

This list of technical objectives and possible solutions is by no means exhaustive. To effectively handle the problem, two basic tasks have to be completed:

- full characteristic of all structural elements within the foundry plant system,
- establishing the relationships between structural elements and the way these are integrated to form a whole, in accordance with the process and production technology with the specified productivity levels.

3. Engineering aspects of compressed air technologies in foundry plants

The engineering aspects are associated with various phases of the casting process using compressed air. Basically, there are several phases (partial processes) involved: mould and core preparation, pneumatic transport, operation of controlling and actuating systems, corrosion control, ornamental painting of castings, ventilation and air-conditioning both individual and on the premises of the foundry plant.

Regardless of this categorisation of partial processes, of particular importance are the functions to be executed using compressed air technologies. In certain cases compressed air is in direct contact with technological materials, in others no contact is established as there are some intermediate elements (indirect action).

The first group of processes includes the mould and core preparation, where the compressed air energy is utilised in handling of the core or moulding sand, to compact it in moulds or core boxes and to transport loose materials. These processes are accompanied by physical and chemical phenomena: formation of the mass-air stream with a variable concentration, filtration, pressure, compaction. In some groups of sand mixes chemical reactions will take place as well, negatively impacting on the sand mix quality and, finally, on the moulds and cores. A most specific process is painting, such as spray painting, in which compressed air acts as a carrier forming the air-paint mixture of the specified density. This group of processes also include dust removal and ventilation, the key parameters being: the air balance, air purity, temperature and its physical and chemical composition.

The latter group of processes involving the indirect action of compressed air are observed in all controlling and actuating mechanisms. The distinctive features of those mechanisms are: structural design, kinetic and dynamic characteristics. Depending on their actual design and applications, the mechanisms execute the rotary, progressing, vibrating or jerk motion and perform work: conveying, turning, transferring, compacting, knocking-out, control.

4. Compressed air quality criteria

Compressed air quality is the criterion underlying the design of compressed air systems. To satisfy the quality criteria, the following aspects have to be addressed [6]:
a) engineering and design objectives,
  - characteristics of receptors with the specified operational parameters, depending on the process technology,

- design parameters and operating characteristic of air sources- compressor units;
- characteristic of the system location structure, taking into account the division into the integrated and network structures;

b) physico-chemical (initial) condition of compressed air leaving the compressors;
- elevated pressure levels in relation to those required in the receptors,
- elevated temperature,
- contamination,
- moisture contents,

c) physico-chemical condition of air to be used in receptors:
- pressure at the inlet to the receptors;
- moisture content,
- quality-efficiency factor;
- temperature;
- purity level;
- other, such as lubricating properties.

5. Technical aspects of adapting compressed air to meet the requirements imposed by process technology

In terms of technological requirements, the adaptation process involves three basic stages: production, treatment and distribution.

Production; the sources of compressed air include compressor machines, belonging to the group of heat engines. Compression is a dynamic process, depending on the design and operational parameters of compressor machines: compression and efficiency. These parameters determine the performance of the entire compressed air installation. The key aspect to be addressed when selecting a compressor type is the actual demand for compressed air. The analysis of air demand takes into account the process technology and the plan of the foundry plant, with the segregated integrated and network structures within the compressed air installation. the starting point in the analysis is the working pressure at the receptors with the clearly indicated admissible minimum, increased by the pressure loss in the connecting installation. The schematic diagram of the procedure is given in Fig. 2.
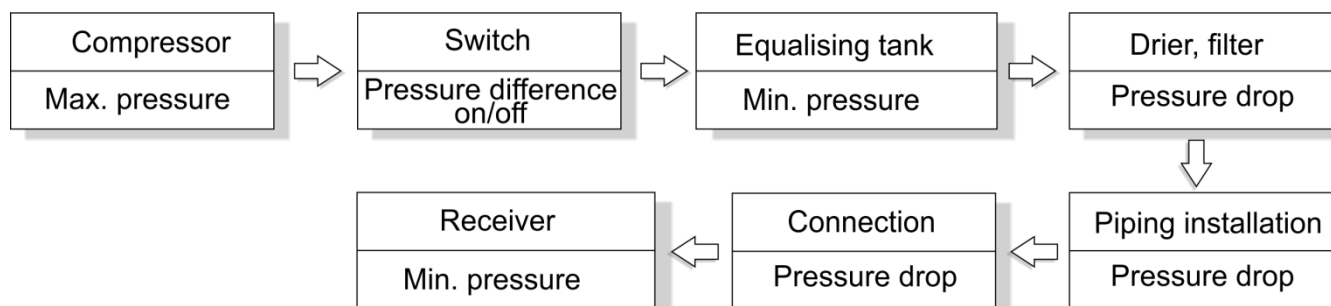

Fig. 2. Determining the pressure levels when selecting compressors- schematic diagram

Another vital parameter is quantitative demand for air, taking into account the utilisation factor and the receptors' concurrent operation. The utilisation factor is expressed as the ratio of the real operation time to the nominal time whilst concurrency means that the "sum" of operating receptors has to be considered within the same period of time. The total demand should take into account the potential leaks, which often occur in practical applications. One of the key components of the system is an equalising tank, its volume being a major parameter. It acts as an air cooler and separator of precipitate, it damps the pulsation and becomes a buffer when the air intake becomes uneven or too much increased.

Treatment involves all processes aimed to change the physical and chemical properties of air and adapt it to the process requirements. Air treatment proceeds in various components of the compressed air line. Their design and operating principles are largely dependent on the scope of the treatment operations and the phenomena that may arise during the flow of compressed air. Air treatment proceeds in the direction coincident with the flow: from

the compressors to the receptors. The schematic diagram of the installation is given in Fig. 3, showing the conceptual design and operating principles of the system.

a)   Water removal

At the outlet from a compressor, compressed air contains a significant amount of water vapour, proportional to air temperature and inversely proportional to pressure. Obviously the water removal process by air cooling in coolers installed behind the compressors will be quite effective. Further cooling, referred to as self-cooling, proceeds in the piping installation. It is recommended that the airflow direction in the installation with respect to the gravity force acting upon the water molecules should be such as to allow water flow to drain holes. Water is then removed through dewatering or by automatic or operated filters.
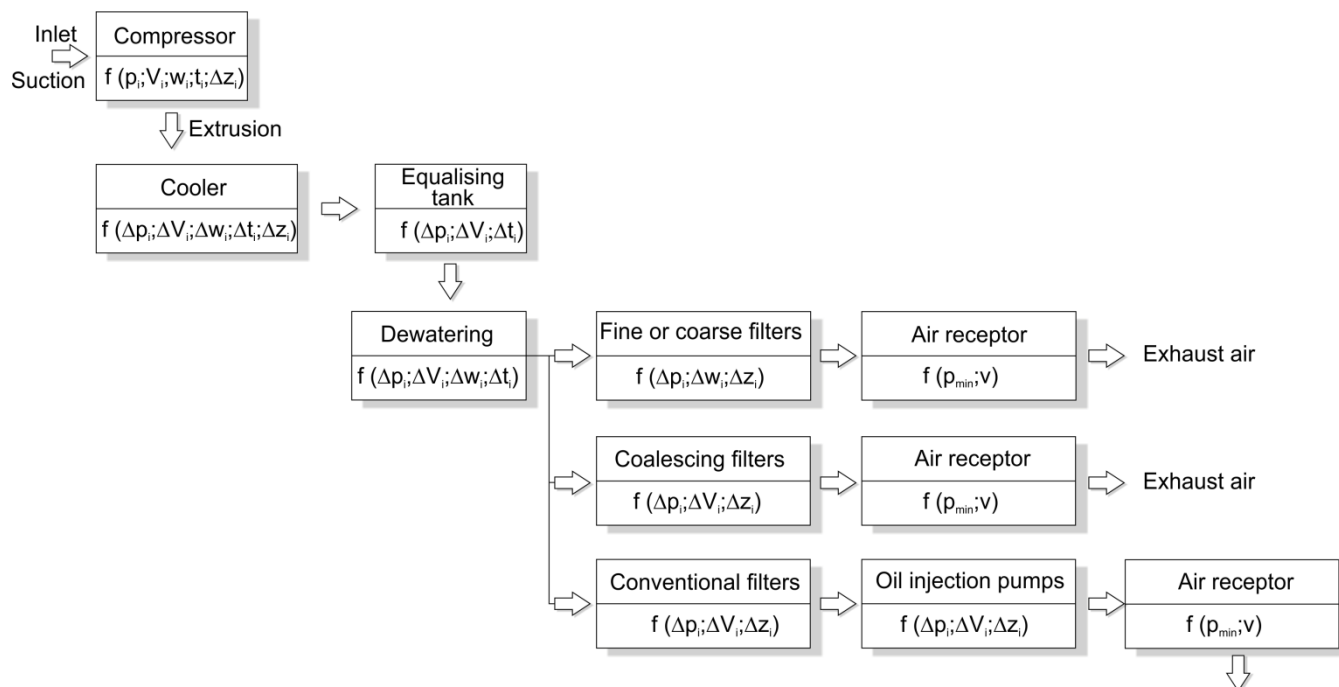
Fig. 3. Schematic diagram of the compressed air installation

b) Removal of contaminants

Compressed air generation involves the suction of air (at the inlet to the compressor), compression action (determined by the compressor's design) and forcing action (outlet from the compressor). At each stage there are potential sources of contaminants: polluted atmospheric air, corrosive compounds, carbon compounds and particles of substances remaining after the assembly operations. The filter types (fine or coarse filters) are selected depending on the size of the contaminants' particles (>40 and 10-25 microns) and the purity requirements.

c) Oil removal

The source of oil are compressors, particularly the oil lubricated types. There is no oil contamination in compressors not requiring oil lubrication. In compressed air installations oil is present in three forms: oil-water emulsions, aerosols and oil vapours. Aerosols contain vary fine particles in the size range 0.01-1 micron suspended in air. They can be removed by coalescent filters mounted in combination with standard filters. When air is contaminated with oil vapours, adsorption filters are required and they are widely employed in the food processing or pharmaceutical sector.

d) Over pressure protection

Compressed air receptors are adapted to operate at the admissible working pressures, depending on their actual design. Any deviation from the specified pressure value produces negative impacts. At elevated pressures, the production and maintenance costs are increased, when the pressure is too low, the operation of the installation becomes ineffective. In order to maintain the optimal pressure levels, reduction valves need to be provided that keep the output pressure constant, regardless of the inlet pressure levels. The input value is determined by the control

characteristics, the output pressure is defined by the flow characteristics. An effective method of eliminating too high pressures at the outlet is to control the compressors' operation within a narrow pressure range and to adjust the air demand to the requirements of particular receptors.

e) Enhancing the lubricating properties

In the context of quality assurance, it is required that certain lubricants- oil substances should be admitted in the installation. It is necessary when the machines are operated in the kinetic and dynamic load modes. When the lubrication conditions are not satisfied, the resistance to motion is increased and the wearing is enhanced, which reduces the service life of the machine. Oil can be introduced into the system by one of the two methods: by spraying or through the use of injection pumps. Spraying gives rise to formation of an oil mist or micro-mist suspension in the air stream. In the case of lubricating systems, the lubricant is supplied to the definite spots which, because of their complex geometry, cannot be reached by air.

Distribution; proceeds in the network system comprising: the main collector connecting the tank with the main pipeline, service lines supplying the ultimate reception points and the receptor devices. It is recommended that the lines should be connected to the main pipeline from above so that the precipitate or contaminants should not get to the receptors. The basic criterion considered when designing the network is the flow rate and the pressure drop. Of particular importance is the pressure decrease due to the resistance to motion caused by the pipeline (due to its diameter, pipe connections, presence of corners), by internal air friction and relative friction of air with respect to the pipe and by flow resistance due to the presence of air treatment system components. The presence of any leaks is detrimental for the performance of network distribution. They are encountered at

connection points or when flexible hoses or cut-off valves get damaged.

5. Summing-up

Procedures employed in design of compressed air systems are based on the adopted criteria. Engineering criteria that have relevance to the design of structures are the basis for an integrated set of technologies and processes realised through technical equipment and energy supply. In the case of a compressed air system, optimisation involves the design of localities of particular objects and their connections via pipelines. Thus formed system is associated with the flow structure. Technological criteria include air quality, defined as the physical and chemical condition of air to be supplied to the receptor devices. The quality assurance involves three major stages: air generation, treatment and distribution. Those criteria underpin the rational design of a compressed air installation.

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