Measurements of geometry of internal flues in multi-flue chimneys

Edyta PUNIACH

AGH University of Science and Technology, Faculty of Mining Surveying and Environmental Engineering, Krakow, Poland
E-mail: epuniach@agh.edu.pl

Abstract

Industrial chimneys are commonly used in industrial plants. Over the years, their design has been constantly modernized. Currently, multi-flue chimneys are mainly built. Although the structure of industrial chimneys is subject to continuous changes, certain surveys performed during periodic inspections of their technical condition are not modified. The issue of examining deformation of internal structural elements in multi-flue industrial chimneys is omitted in the diagnosis of those objects. It is worth emphasizing that these elements are indeed more frequently deformed and damaged than external reinforced concrete shells, whose technical condition is regularly monitored.
In the study, an attempt was made to prove that regularly performed measurements of structural elements in multi-flue industrial chimneys are necessary to fully assess safety of these objects. The problem of influence of deforming internal load-bearing platforms on deflection of the flues in multi-flue chimneys has been discussed, as well as the issue of their deformation and damage. The author also suggested surveying methods to measure geometry of the internal flues, due to extremely difficult conditions inside the structure.

Key words: multi-flue chimneys, displacement measurements, periodic inspections of technical condition of structures

1 INTRODUCTION

Building structures are subjected to the influence of numerous internal and external factors. They result in the occurrence of changes in spatial positioning of structural elements of an object, which can prevent its proper operation. In order to counteract such situations, it is necessary to obtain information about geometrical changes which building structures or their parts undergo. This is particularly essential in the case of objects of exceptional importance, whose failure or catastrophe threatens the lives of people or carries the risk of environmental damage. Therefore, implemented actions should be aimed at controlling structure's resistance, its performance and, above all, verifying the level of object and user safety (Moore, 1992).

Diagnostics of industrial chimneys calls for a reliable assessment of their technical condition. This is a complex process that requires extensive knowledge of the studied structure and cooperation of specialists in various fields. It allows to plan proper range of necessary repair works (CICIND 1993; Barycz, S. et al. 2006; Bhowmik, A.K. 2005; Oruba, R. 2006).

Industrial chimneys are subjected to surveying monitoring, repeated at fixed intervals. These observations aim at assessing stability of a building structure. Changes in the positions of foundations and the load-bearing shell are determined. Current control surveys of multi-flue chimneys are limited only to determining values of the above mentioned parameters. The problem of surveys of displacements and deformations of internal structural elements of multi-flue industrial chimneys has been neglected so far in assessing technical condition of these objects. This applies to steel or reinforced concrete internal platforms, as well as segments of internal flue linings. It is worth emphasizing that internal structural components of multi-flue chimneys are more often deformed and damaged than their outer reinforced concrete shells, whose technical condition is systematically monitored. This problem was described in detail in (Puniach, E. 2016).

2 TECHNICAL CHARACTERISTICS OF MULTI-FLUE INDUSTRIAL CHIMNEYS

In large industrial plants today, there are multi-flue reinforced concrete chimneys constructed, with a reinforced concrete shell as the main supporting structure of the chimney, which absorbs all the loads acting on the structure. In the case of a large number of flues, these can be two concentric reinforced concrete shells. Inside the chimney, there are flue liners resting on reinforced concrete or steel internal slabs, which are based on chimney shell supports.

2.1 INTERNAL FLUE LINERS

Internal flue liners are usually made of steel or of ceramic fittings (CICIND 1991, 1995; Beaumont, M. et al. 2005; Kremser, B. 2005). If temperature of flue gas does not exceed +80°C, linings made of glass fiber reinforced plastics may be used (Arckless, P. et al. 2005). Regardless of the material which they are made of, they are usually protected from the outside with thermal insulation, which ensures constant temperature of flue gas and allows to maintain correct temperature in the void between the flues and the reinforced concrete shell.

Flue liners can be elements supported on internal load-bearing platforms. Then, they are divided into segments that work independently. Free thermal expansion of lining segments is ensured by horizontal expansion joints at contacts between them. Structures, in which individual sections of liners are suspended, as well as self-supporting flue systems, are also used. In the latter system, the liners are continuous throughout their entire length and supported in the lower part of the chimney, above the flue inlets or at the level of ±0.00 m. Stability of self-supporting flues is ensured by intermediate slabs, which support the flues in horizontal direction and allow their free vertical thermal expansion.

2.2 DAMAGE TO INTERNAL STRUCTURAL ELEMENTS OF MULTI-FLUE CHIMNEYS

Internal structural elements of multi-flue chimneys are subjected to various deformations. Changes in the geometry of internal slabs affect the geometry of flue liners, which is the most common cause of damage to these structures and the resulting repair works.

Girders of load-bearing slabs in multi-flue chimneys are usually designed as freely supported beams, which play an important role in maintaining the safety of the entire structure. The initial deflection of the slabs, prior to their build-up, is due to the dead load of the load-bearing platform structure. It is taken into account when the flue is being constructed. However, further deformations of the slabs resulting from the slabs being loaded by the structure of the chimney flues, imply displacements of the flue segments which are based on them.

Deflections of the load-bearing slabs lead to vertical displacements of the flue liners resting on them which, in extreme cases, may cause their damage. This applies both to beam platforms and to reinforced concrete slabs. The literature deals with this phenomenon, e.g. in (Noakowski, P. et al. 1991; Busch, D. et al., 1994; Ertz, B. et al. 2004). This problem is illustrated in Figure 1, where dashed lines illustrate the flues displaced as a result of deflection of the load-bearing slab. This example relates to a chimney with a single reinforced concrete shell, equipped with ceramic flue liners.

At contact points between flue segments, there are horizontal expansion joints with elastic joint tapes. Expansion joints allow for independent work of the flue segments. If a designed joint opening is too small compared to deflection value of the element, its wall will lean against the platform structure. Initially, this results in ovalization of the circular section of the flue. As a consequence, with the increasing tensile stress, this may lead to the occurrence of damage to the flues, such as cracking of their upper parts, accompanied by creasing of the joint sealant tape (Oruba, R. et al. 2012). This problem mainly concerns multi-flue chimneys with ceramic flue liners.

3 MEASUREMENTS OF GEOMETRY OF FLUE LINERS

3.1 CLASSICAL SURVEYING TECHNIQUES

A 300-meter-high, six-flue chimney was the research structure on which classical surveying techniques were tested to determine geometry of the flue liners. The chimney's load-bearing structure was a reinforced concrete shell with six steel flue liners of 6.50 m in diameter. They were thermally insulated with mineral wool. The flues were self-supporting elements, installed at the level of ±0.0 m. Additionally, they were attached to the reinforced concrete shell at intermediate levels using special steel structures. The chimney was equipped with steel internal slabs, which were spaced at intervals of about 30÷40 m. The slabs served exclusively to determine the position of the flue liners and current maintenance. They were covered with steel sheets.

The performed surveys of the chimney were primarily aimed at determining the shape of the axis of the steel flue liners. External thermal insulation blocked off direct access to the load-bearing structure of the flues. Therefore, steel rings which stiffened the flue liners were subjected to the surveys. It was predetermined that the center of the steel ring coincided with the center of the flue (two concentric circles). Such rings were located on three internal platforms (+106.8 m, +214.8 m, +286.7 m), and at these levels, vertical deviation of the flue axis was determined.

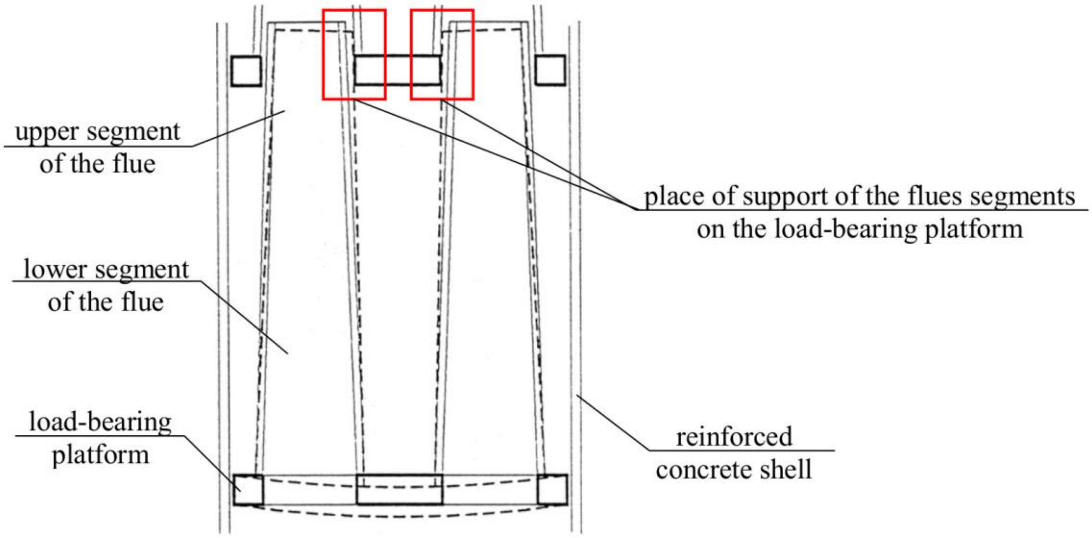

Fig. 1 Influence of deformation of load-bearing platform girders on deflection of flue segments (Noakawski, P. et al. 1991)

In order to carry out planned surveys inside the structure at a level of ±0.0 m, a spatial geodetic control was established and measured. Location of the points and shape of the angular-linear control network depended on dimensions of the structure and development of the space inside the reinforced concrete shell. In addition, a function to be met by the established control was taken into consideration. Its task was to topographically tie controls at the levels at which measurements of the flue verticality were planned.

The next stage of the works was to copy the height and plane coordinates from the level of ±0.0 m to the three intermediate levels where flue verticality control was performed. Two points of the measurement control were established at each level, defining their spatial coordinates in the defined coordinate system. These points then became reference points for the angular-linear control networks established on the platforms. The adopted methods of establishing, tying and measuring controls at the measurement levels inside the chimney allowed to obtain the mean error of the point position at the level of ±10 mm, which directly affected the accuracy of determining deflection of the vertical flue axis.

The method used to measure the internal geometry of chimney flues involved surveying a set of points on the perimeter of the steel rings of each flue liner (Puniach, E. et al., 2013; Puniach, E. 2016). The instrument used for the implementation of the surveys was the Leica TCRP1200 total station. Measurement points were distributed evenly along the entire perimeter of the examined element. A minimum of three points were to be measured at one level of the flue. In order to increase reliability of the survey, the size of the observation data sets was raised to 7÷18 points at each perimeter. Based on the obtained measurement data, coordinates of the centers of the circles approximating cross-sections of the flues were determined. Final deflection of the flues from their vertical axes was calculated, assuming that the reference level is the lowest measurement level. The accuracy of fitting circles into measurement points was determined using the residual variance estimator. The internal accuracy of the applied measurement method (analysis of dispersion from the mean value) was calculated. Table 1 summarizes the obtained results, i.e. deflection of the flue axis along the X axis (w_x) and along the Y axis (w_y), as well as the resultant deflection (w) together with their mean errors. Values of deflection of the outer reinforced concrete shell, determined by the classical method of surrounding tangents, from three positions of the instrument, are also summarized in Table 1.

Table 1. Summary of surveyed deflections from vertical axis of the flue liners and of the reinforced concrete shell of the chimney (Puniach, E. 2016)

Structure	***H***	**Parameter**						
		w_x	w_y	w	A_w	σ_{w_x}	σ_{w_y}	σ_w
	m	m	m	**m**	gon	mm	mm	mm
Flue No. 1	+106,8	0,000	0,000	**0,000**	-	-	-	-
	+214,8	-0,221	0,028	**0,222**	192,0	15,3	10,5	15,3
	+286,7	-0,145	0,101	**0,177**	161,3	16,0	9,8	14,3
Flue No. 2	+106,8	0,000	0,000	**0,000**	-	-	-	-
	+214,8	-0,065	0,118	**0,135**	132,0	16,0	15,9	15,9
	+286,7	0,059	0,140	**0,152**	74,6	11,9	13,4	13,2
Flue No. 3	+106,8	0,000	0,000	**0,000**	-	-	-	-
	+214,8	-0,054	0,207	**0,214**	116,2	7,5	9,2	9,1
	+286,7	-0,062	0,303	**0,309**	112,8	7,6	9,5	9,4
Flue No. 4	+106,8	0,000	0,000	**0,000**	-	-	-	-
	+214,8	-0,138	0,056	**0,149**	175,5	14,4	9,0	13,8
	+286,7	-0,105	0,194	**0,220**	131,6	14,1	8,2	9,9
Flue No. 5	+106,8	0,000	0,000	**0,000**	-	-	-	-
	+214,8	-0,174	0,136	**0,220**	157,8	7,3	13,0	9,9
	+286,7	-0,061	0,149	**0,161**	124,7	4,2	10,4	9,8
Flue No. 6	+106,8	0,000	0,000	**0,000**	-	-	-	-
	+214,8	-0,217	0,173	**0,278**	157,2	14,7	17,4	15,8
	+286,7	-0,158	0,189	**0,246**	144,3	14,4	17,2	16,1
Shell	+50,6	0,000	0,000	**0,000**	-	-	-	-
	+111,2	-0,003	0,012	**0,012**	115,6	6,4	3,3	3,6
	+238,5	0,002	0,093	**0,093**	98,6	15,1	7,9	7,9
	+285,6	-0,019	0,149	**0,150**	108,1	12,4	6,4	6,6

The maximum value of the resultant deflection of flue liners was 309 mm (flue No. 3, +286.7 m), with a mean error of ±9.4 mm. Based on the values of the calculated azimuths of the resultant deflections (A_w), it can be stated that all the flues deflected in the south-east direction. Displacement of the top of the reinforced concrete load-bearing shell reached 150 mm (±13.9 mm) and had an eastern direction.

3.2 TERRESTRIAL LASER SCANNING

The next object of the study was a chimney with a height of H = 150 m. Its main load-bearing element was a reinforced concrete, cylindrical shell, 11.80 m in diameter, taking over the load of steel internal platforms and transferring them to the foundation. In the lower part of the chimney, up to the level of +49.50 m, there was an inner cylindrical, reinforced concrete shell with a diameter of 8.11 m. Flue gas was drained off through one internal ceramic flue liner. The flue liner was divided into segments. There were two segments within the inner reinforced concrete shell: the first one from the level of +10.00 m to +25.80 m, and the second one from +25.80 m to +50.10 m. Higher, up to the level of +150.00 m, ceramic flue liner was self-supporting and consisted of three segments. The lowest segment rested on the top part of the inner reinforced concrete shell. Two higher segments were based on annular reinforced concrete beams, and the beams on steel girders of the platforms carrying loads to the reinforced concrete outer shell. Steel slabs occurred at the levels of +83.50 m and +116.50 m.

Horizontal expansion joints of individual segments of the ceramic flue liner were sealed with elastic joint tape.

The method of terrestrial laser scanning was used to survey geometry of the flue liners (Puniach, E. 2016). In this case, FARO Focus 3D was used. The measurements were carried out at four levels: ±0.00m, +49.50m, +83.00m and +116.50m. This allowed for recording geometry of the outer and inner shells, and of the flue. Scanning was performed at full visual field (360° x 305°) of the instrument, with a resolution of 3 mm x 3 mm, at a distance of 10 m. In order to merge and mutually orientate point clouds from all 22 measuring stands of the instrument inside the structure, a scanning control network of 68 points was established. Due to the shape of the object and the slabs being built up with platforms, it was impossible to install and survey common targets for the stands of the instrument located at different levels. Therefore, merging of the captured data sets into one cloud representing the entire structure was possible by determining spatial coordinates of the scanning control points in a uniform coordinate system. Thus, two points of a geodetic control were established on each platform, whose spatial coordinates were determined in the orientation process. The mean square position error of a point of the control was ±5.8 mm, and for the determined heights, this parameter reached a value of ±2.9 mm. Two marks of the control, stabilized at the height of each slab, then served as reference elements for angular-linear survey networks established at all measurement levels. The captured data allowed for the adjustment and calculation of transformation parameters for each stand of the scanner. As a result, it was possible to merge (record) the obtained points clouds. The mean value of the fitting error was ±4.7 mm.

A set of points captured by laser scanning method, representing the reinforced concrete outer and inner shells of the chimney, and the flue, was analyzed to determine geometry of the studied elements. Therefore, coordinates of their centers were defined at the predetermined observation levels, which formed the basis for determining deflection components of the flue liners and the reinforced concrete shells, relative to the lowest measurement level. Deflection components of the flue segments were calculated with a mean error of ±13.6 mm (mean square error), and their maximum values of 22 mm on average were comparable for each of the analyzed elements.

Another significant factor which affects operational reliability of the chimney is mutual location of neighboring parts of the flue, separated by expansion joints. Figure 2 illustrates results obtained from the analysis of horizontal cross-sections made by a set of points obtained by laser scanning method. The biggest difference between the position of the upper part of the lower segment of the flue liner, and the lower part of the upper segment, is 26 mm. The difference was recorded to merge the flue elements at +83.00 m.

Based on the cross-sections made with the horizontal plane by the point cloud, the shape of the vertical axis of the reinforced concrete shells was also determined. A graphical illustration of the obtained results is demonstrated in Figure 2. The mean square error of the determined resultant deflection was estimated at ±12.6 mm for the outer shell and ±10.5 mm for the inner shell. The top of the outer shell is deflected by 30.2 mm towards 365.9 gons (w_x = 25 mm, w_y = -17 mm) relative to its base.

a) b)

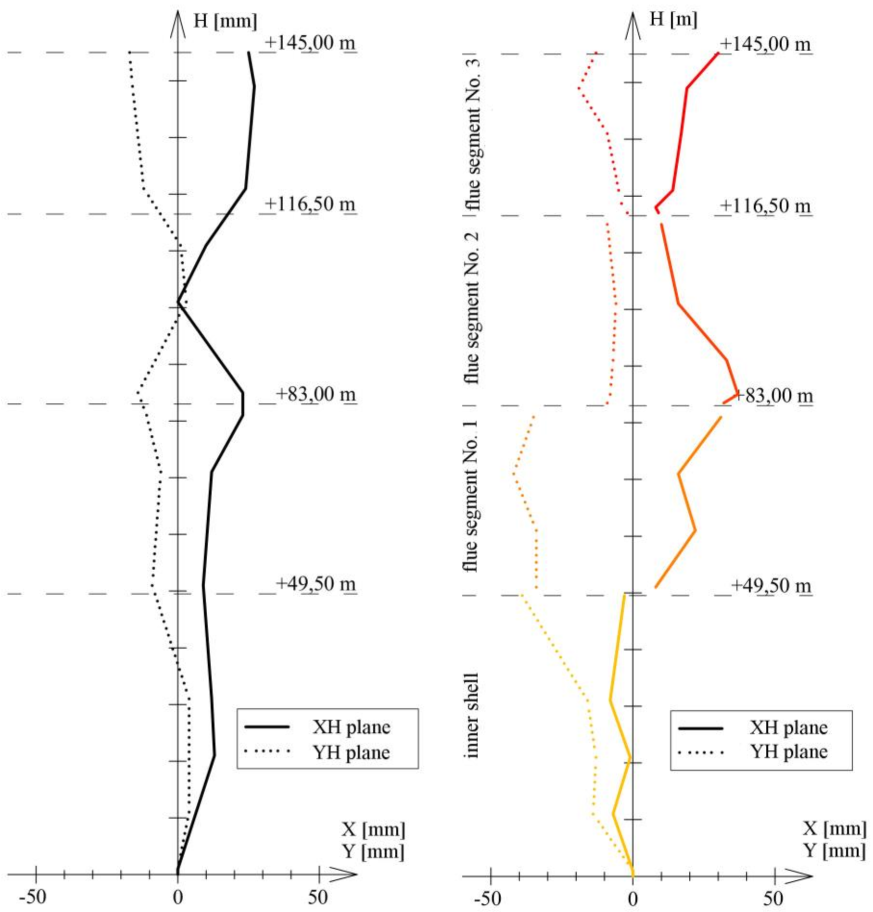

Fig. 2 Survey results for the chimney H=150 m: a) displacement of the outer shell; B) mutual location and shape of the axis of the inner shell and of the flue segments (Puniach, E. 2016)

4 SUMMARY

Chimneys are essential elements of the technological process of large industrial plants. Therefore, they must exhibit high resistance and operational reliability. Modern multi-flue chimneys have a complex design. Inside reinforced concrete shells, there are steel or reinforced concrete slabs, which support flue liners. Uneven deflections of slab girders may cause displacement of the flues. In extreme cases, this may result in severe damage to the flue liners and, in consequence, a need to eliminate the chimney from the process and closing down a plant to carry out repair works.

Accurate assessment of technical condition of the flues and properly planned reconstruction works are therefore essential for ensuring safety of these structures and continuity of their operation. Surveys of verticality of internal flue liners constitute a valuable source of information on geometry of the monitored elements. The scope of their monitoring should be modified, depending on the design solutions of the chimney.

The surveys which were described in this paper, used not only classical surveying techniques but also laser scanning, which confirmed its usefulness for this purpose. The use of laser scanners makes it possible to capture a very large set of data on geometry of the surveyed structural components, with only a slightly greater effort compared to traditional methods.

Thus, it may be concluded that laser scanning is especially helpful when performing complex geodetic measurements inside multi-flue chimneys.

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