SUSTAINABLE STEEL CHIMNEY DESIGN FOR COMBINED HEAT AND POWER PLANTS

Herbert Schmidt
University of Essen/Germany
Ufuk Kocabiyik
Consultants Prof. Schmidt & Partner, Essen

Abstract

It is a well-established technique to separate in a chimney the duct function from the load-carrying function by means of a stainless steel liner. In Combined Heat and Power plants the liner is, depending on the operational design, exposed to more or less severe differential temperature effects. In order to get optimal benefit from the high corrosion- and heat-resisting properties of the stainless steel, the liner has to be structurally designed in a way that the thermal gradients cannot cause significant local buckling. Experiences from recent buckling damage case studies are transformed into a constructional methodology and concrete design recommendations. They are illustrated by an example.

1 INTRODUCTION

An important feature of modern natural gas based Combined Heat and Power (CHP) plants is their optimal energy efficiency which is a considerable contribution to a sustainable handling of our natural resources. In a first process stage, gas turbines produce electricity, eventually combined with succeeding steam turbines. This first stage emits hot flue gas with temperatures up to 550°C. In a second process stage, the hot gas is used to produce heat for urban or industrial purposes in a heat recovery steam generator. After this second stage, the flue gas has temperatures of around 100°C (called “cool“ in the present context). However, there are periods in the operation of such power plants where the hot flue gas has to be released directly into the air, bypassing the waste-heat boiler of the heat recovery steam generator, e.g. when no heat is needed.

The logical consequence would be two chimneys, one for the hot and one for the cool flue gas. Both of them would, because of corrosion reasons, require stainless steel liners. However, the resulting pair of free-standing double-skin steel chimneys of up to 75 m height would represent a considerable cost factor. Therefore, it suggested itself to combine the two flue gases into one single chimney in order to reduce the building costs, and also to minimize the architectural impact on the urban appearance. But that leads inevitably to temporary mixed gas situations, either for a short time when switching from one operation type to the other, or over longer periods under a planned mixed operation. It turned out to be impossible to regulate the gas mixing process in a manner that makes the liner tube heat up and cool down perfectly uniformly, i.e. only extending vertically and radially in an axisymmetric manner, but without global bending of the liner tube.

That caused in recent years in several power plants severe local buckling damage in such liners so that they became pervious because of cracks at excessively folded local buckles. The consequence was that the hot gas gained access to the inner surface of the outer structural shell creating a serious safety problem. Therefore, the damaged liners had to be repaired or completely replaced, respectively. The consequence of these bad experiences should not be to come back to the expensive two-chimneys solution, but to develop structural forms for the stainless steel liner which, on the one hand, provides the primary duct function, but on the other hand avoids buckling damage by the unavoidable thermal effects. The present paper deals with this constructional task for an engineer designing the chimney structure for a CHP plant.

2 STATE-OF-THE-ART OF STAINLESS STEEL LINERS

2.1 Constructional layout of the liner

A lining system within a structural steel windshield of a free-standing chimney may on principle be realized [1, 2, 4] as one of the three basic types (a) top hung liner, (b) sectional liner or (c) base supported liner. In type (a) the whole liner is in tension. However, the ostensible advantage of avoiding axial buckling considerations under self-weight vanishes in case of thermal effects (see 2.3) which cause axial compressive stresses from overall bending – regardless of whether the liner is hanging or standing. On the other hand, the great disadvantage of having to provide the liner with an expansion joint of large vertical movement capacity at its bottom near the duct entry usually rules this system out. The disadvantage may be reduced when choosing type (b) where the liner is composed of a number of sections each suspended (or supported) from floors at various levels. However, the tightness requirements at each of the sectional expansion joints make this liner type rather problematic. In the authors' opinion, type (c) should normally be the optimal one: The continuous tube has no tightness problems, and the large vertical expansion movements (relatively to the outer structural shell) may easily be accomplished at the top. In the rest of this paper, only base supported liners will be considered.

Regarding lateral guidance of the liner against the structural shell, two basic arrangements are possible, depending on the column slenderness of the liner and on the execution method (Figure 1). In system A the liner stands free over its complete height. Only at the top it has to be guided laterally. This arrangement implies that the height/diameter ratio is large enough to prevent column buckling and that no guidance is needed, neither during execution nor with respect to the coupled deformations from wind loading on the structural shell. During execution no guidance is needed when in a large chimney the liner is erected sectionwise by site-welding in its final vertical position within the structural shell. Contrary to that, in system B the liner has to be laterally guided at various intermediate levels, either because it is prefabricated as a whole or in a small number of courses (two or three) and is inserted into the structural shell in horizontal position, or because structural design considerations (column buckling, wind deformations) require the intermediate horizontal support.

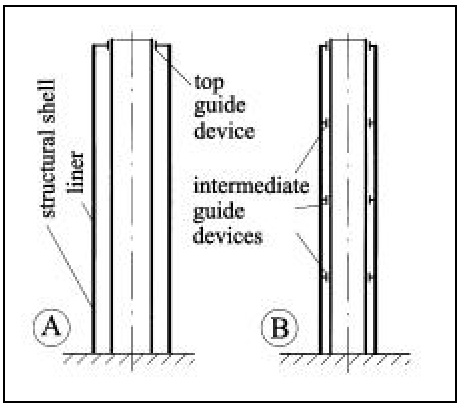

Figure 1 Basic arrangement systems for the lateral guidance of base supported liners

2.2 Thermal actions on the liner

The European Prestandard for the design and execution of steel liners in free standing chimneys [2] gives some guidance for the treatment of thermal actions when designing the liner. Especially the effects of differential temperatures in the flue gas stream are dealt with. In case two partial streams of different temperatures T_1 and T_2 are fed into the liner from opposite sides, rules are given how to estimate the global bending effective temperature gradient ΔT and its distribution over the liner height in the form of an exponential function. A rough estimate for the secondary shell stresses from differential temperatures is also given. If the liner handles only a single gas stream with nominally uniform temperature, a minimum "thermal imperfection" value of $\Delta T = 15K$ at the duct entry is recommended. The authors are not familiar with the background of these rules and their eventual verification by measurements.

2.3 Experiences from local buckling damage cases

The authors had the opportunity to analyse a number of the damage cases mentioned in the introduction [5, 8]. In all cases the local buckling was of the axial compression shell buckling type, and in all cases it was initiated by differential temperatures in the flue gas stream although the operational and constructional design concepts were rather different. The operational design concepts reached from deliberately mixing the hot and the cool flue gases within the liner (causing severe differential temperatures in the liner wall) to mixing them in special devices before they enter the liner as a single gas stream (still causing unavoidingly differential temperatures in the form of thermal imperfections). The constructional design concepts reached from system A (Figure 1) with a circular assembly of carefully designed pendulum hangers as base support to system B with a circular assembly of loosely resting brackets as base support and as many as four intermediate lateral guide devices in the form of rolling or sliding bumpers with or without elastic springs.

One of the cases with system A has been published in detail in [5]. Figure 2 illustrates the damage process of this liner into which both of the flue gases, the hot one and the cool one, are introduced concentrically from below. The hanger-supported section at the base support represented for the vertical tubular beam a full bending restraint (Figure 2b). The thermal imperfections produced a foot bending moment M_E. An elementary analysis shows that an assumed bending effective temperature gradient ΔT across the diameter (see Figure 2a) having an order of magnitude as small as 15K and decreasing to zero at the top of the liner would already cause the observed damage which included local buckling above the support (phase 1). With further increase of ΔT the statical system acted determinately (Figure 2a); the tube could now deform unrestrained within the limits of the ventilated space between structural shell and liner (phase 2). The lower sliding bumpers then lost their horizontally supporting effect (can not be deepened here), and the tube could deform even more (phase 3). The main remedial measure when reconstructing the liner support was to include piles of cup springs between the hangers and their bearings. That lead to the statically determinate beam system of Figure 2a from the very beginning.

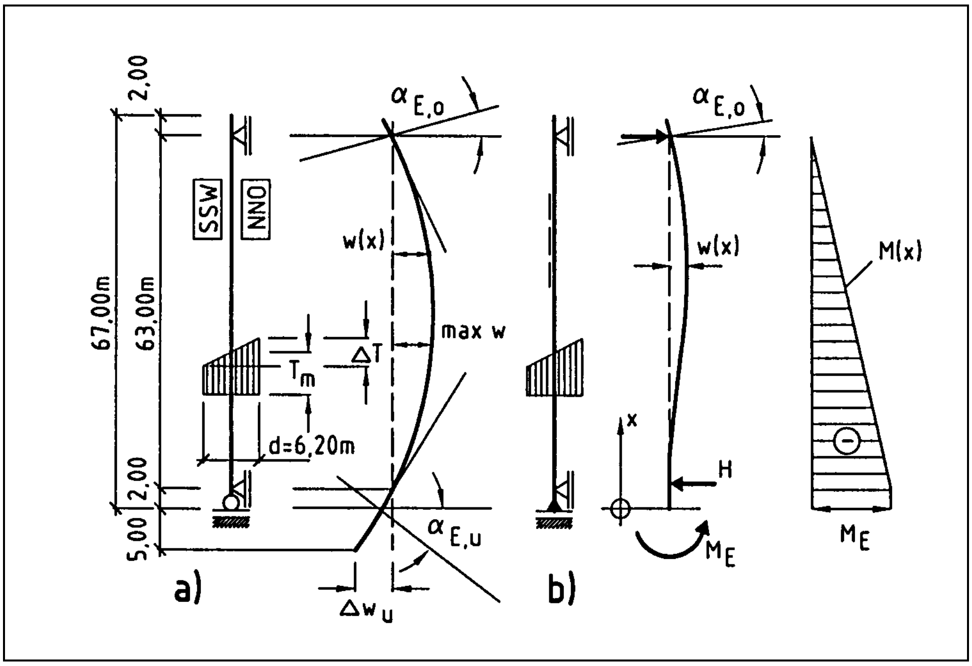

Figure 2 Statical tubular beam systems of a base supported liner (according to Figure 1-A) in which local buckling occurred: a) hinged support, b) bending restrained support

The common general experience of all bucking damage case studies of the authors was the obvious “urge” of the liners to get rid of statical restraints by means of local buckles. The larger the differential temperatures were and/or the stronger the restraint was and /or the larger the r/t-ratio of the liner tube was, the deeper were the buckles and the more did they form complete semicircular patterns on the bending compression side which provided the liner tube with its “wanted” hinge. In one case as many as three such “buckling hinges” developed, thus eliminating three redundant bending moments. The operational consequences reached from leaving the buckles in the liner wall and checking their depths after every heating period (in case of moderate depths) to immediately replacing the buckled liner section by a new and more properly designed one (in case of excessively folded buckling patterns with great depths and with cracks on sharp inward ridges).

A secondary experience was that lateral guide devices tend to promote the local buckling from tubular bending when their clearance is too small. In this case the radial restraint from thermal expansion produces inward eccentricities for the axial membrane forces in the cylindrical shell. The same occurs when the lateral guide devices have elastic spring elements in order to bridge the clearance during the cool state and when these spring elements are too stiff.

2.4 Local buckling design of shells made of stainless austenitic steel

Relevant design standards for structural steel shells (e.g. [3]) are not applicable in a straightforward manner to shells made of austenitic steel. The reason is that the design rules are calibrated against non-alloy structural steels with their well-defined material properties E and f_y. However, austenitic steels have markedly nonlinear stress-strain-curves, particularly at elevated temperatures. In practice this is usually accounted for by conservatively introducing a fictitious secant modulus instead of E into the design procedure. K.T. Hautala has developed an improved method for an equally economic and safe buckling design of shells made of austenitic steel [6, 7, 10].

3 STRUCTURAL DESIGN OF STAINLESS STEEL LINERS

3.1 Design Recommendations

The most important finding from the authors' buckling damage case studies is that the structural engineer should not rely on the predictions of his process engineering collegues as far as the regularity of the temperature distribution within the flue gas is concerned. Even when both of the flue gases, the hot one from the bypass and the cool one from the heat recovery steam generator, enter the liner concentrically from below, i.e. when during combined operation or during switching action the two gas streams are mixed before entering the liner, this is apparently not a "single gas stream" as meant by ENV 13084-6 where a thermal imperfection assumption of $\Delta T = 15$ K is recommended (see 2.3). At least the double value is recommended by the authors for chimneys of CHP plants.

The basic structured design principles should be:

- Make the tubular beam system of the liner statically determinate; if that is not possible, shift the statical indetermination to the upper regions where the temperature irregularities become smaller.
- Make sure that the theoretically assumed support conditions are accurately realized by the construction; a hinged support must really be rotatable, a displaceable support must really be free to slide.
- Give the liner tube any free space to develop its global thermal deformations without being forced to transform them into thermal stresses.

For a base supported liner of system A the first two principals are under no circumstances met by some of the traditional solutions: A loosely resting (not welded) circular liner edge or circular group of brackets is not a hinged support, and a pair of bearing steel plates free to slide on each other are not a displaceable support. Figure 3 shows two constructional solutions for a hinged support, as recommended by the authors. They have proved to work in reconstructed liners in connection with the damage cases mentioned earlier in this paper. The first solution (Figure 3a) is a circular assembly of inclined pendulum hangers by which the liner is connected to the structural shell and in which cup spring piles with defined low stiffness rates are interposed between the hangers and their bearings. The second solution(Figure 3b) is a corrugated plate compensator with low angular but sufficient axial stiffness which is welded between two courses of the liner. An accurate displaceable support may easily be realized by interposing slide material (e.g. based on PTFE) between the structural bearing plates.

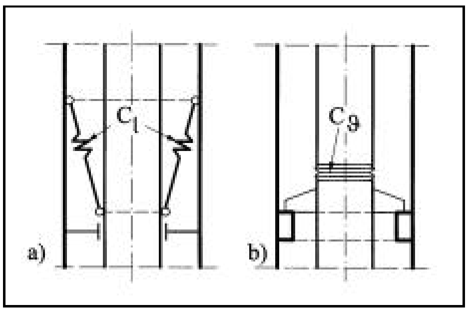

Figure 3 Constructional solutions for a "hinged support" of a base supported liner (schematically): a) Pendulum hangers with included (prestressed) cup spring piles, b) corrugated plate compensator

In a base supported liner of system B one further corrugated plate compensator has to be included into the liner tube at every intermediate lateral guide level, unless it can be proved that the axial compressive stresses caused by the maximum tubular bending moment at the lateral support is far enough below the local shell buckling resistance of the liner. An example for system B is presented in the next section.

3.2 Design Example

Figure 4a shows a CHP plant chimney of 40 m height in which the cool flue gas enters the liner from the side while the hot flue gas is introduced from below. The decisive temperature load case occurs when, after a bypass operation period, the plant switches to heating operation. In this stage the uniformly heated-up liner is exposed to a differential temperature situation of which the tubular bending component ΔT is assumedly distributed as shown in Figure 4b (see also [2]). It is furthermore assumed for this example that the execution concept requires two intermediate sets of rolling bumpers, one 2m below and the other one 2m above the site-bolted flange joint (see Figure 4a). The resulting statical beam system with four couplings between the structural shell (at ambient temperature) and the liner (at 550 °C) is shown in Figure 4b. It includes two corrugated plate compensators, one in order to eliminate the restraint moment above the vertical support (see Figure 3b), the second one to eliminate the hogging moment at the lower one of the two intermediate horizontal supports.

The resulting bending moments in the liner are plotted in Figure 4c. The shell buckling check at the upper intermediate horizontal support (M = 453 kNm) according to ENV 1993-1-6 [3] reads as follows:

σ_x = $453 \cdot 10^6 / (\pi \cdot 1500^2 \cdot 4) = 16{,}02$ MPa

σ_{xRc} = $0{,}605 \cdot 161{,}5 \cdot 10^3 \cdot 4 / 1500 = 260{,}6$ MPa

$\bar{\lambda}_{Sx}$ = $(127 / 260{,}6)^{0{,}5} = 0{,}698$

α_x = $0{,}62 / [1 + 1{,}91\,(1/16)^{1{,}44} \cdot (1500 / 4)^{0{,}72}] = 0{,}176$

$\bar{\lambda}_{xp}$ = $(2{,}5 \cdot 0{,}176)^{0{,}5} = 0{,}664 < 0{,}698$

χ_x = $0{,}176 / 0{,}698^2 = 0{,}361$

ψ = 0,75 [10]

σ_{xRk} = $0{,}75 \cdot 0{,}361 \cdot 127 = 34{,}4$ MPa

$\sigma_{xRd} / \sigma_{xEd}$ = $34{,}4 / (1{,}5 \cdot 1{,}1 \cdot 16{,}02) = \underline{1{,}30 > 1}$ ✓

As can be seen, there is no need for a further compensator at the second intermediate horizontal support. The deformations of the liner tube from ΔT are shown in Figure 4d. It can be seen that the ventilated space between the structural shell and the liner should provide the hot liner (i.e. the radially extended liner) with at least $1{,}5 \cdot 28 = 42 \approx 50$ mm clearance for global bending deformations. The expansion joint at the bottom of the liner must allow for $1{,}5 \cdot 36{,}7 = 55$ mm lateral displacement of the tube end. The two compensators should have an allowable rotation angle of at least $1{,}5 \cdot 0{,}43 = 0{,}65° \approx 1{,}0°$.

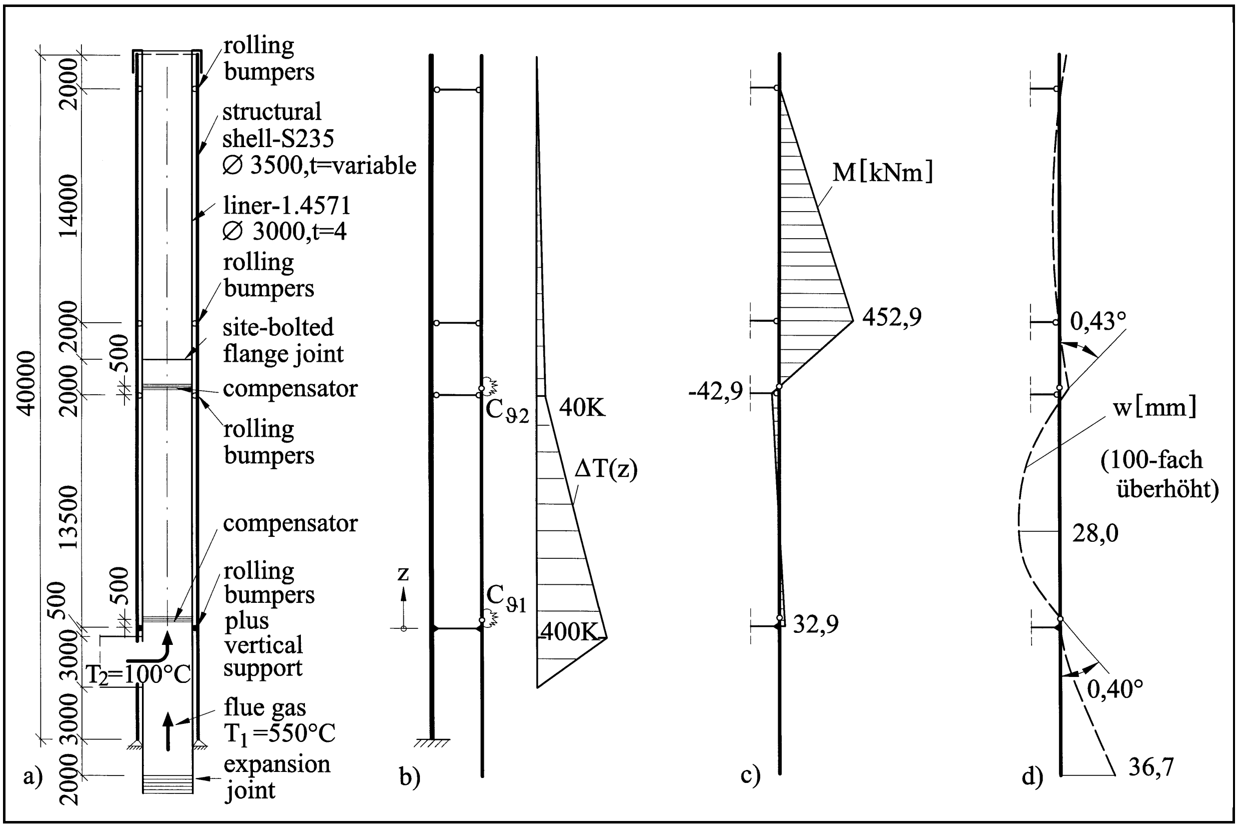

Figure 4 Design example: a) Constructional layout of the liner, b) statical tubular beam system and ΔT-distribution, c) bending moments in the liner, d) deformations of the liner

4 CONCLUSIONS

(1) One single double-skin chimney for both the hot and the cool flue gases in a CHP plant is a reasonable contribution to sustainable steel construction.

(2) To really achieve the sustainability the stainless steel liner has to be structurally designed in a way that makes it immune against local buckling from differential temperatures in the gas stream.

(3) Experiences from damage case studies show that the tubular beam system of the liner should be statically determinate or, if that is not feasible, as little redundant as possible.

(4) The paper gives recommendations how to achieve this constructionally; an example illustrates the application.

(5) The recommendations may also be applied to the task of replacing the brick lining in an old concrete chimney by a stainless steel tube [9].

5 REFERENCES

[1] ENV 1993-3-2:1998: Eurocode 3 - Design of steel structures - Part 3-2: Chimneys.

[2] prEN 13084-6 (Draft December 1999): Free standing chimneys - Part 6: Steel liners.

[3] ENV 1993-1-6:1999: Eurocode 3 - Design of steel structures - Part 1-6: Supplementary rules for shell structures.

[4] Petersen, C., Stahlbau, 3. Auflage, Braunschweig/Wiesbaden, Vieweg, 1993.

[5] Schmidt, H., Schäden am Innenrohr eines Doppelmantelschornsteins infolge “thermischer Imperfektionen“, Stahlbau 67, 1998, 452-458.

[6] Hautala, K.T., Buckling of axially compressed cylindrical shells made of austenitic stainless steels at ambient and elevated temperatures, Dr.-Ing. thesis, University Essen, 1998.

[7] Hautala, K.T., Schmidt, H., Buckling of axially compressed cylindrical shells made of austenitic stainless steel at ambient and elevated temperatures, In: Light – Weight Steel and Aluminium Structures, 233-240, Amsterdam, Elsevier Science, 1999.

[8] Schmidt, H., Kocabiyik, U., Temperature-initiated buckling phenomena in stainless steel flue gas liners of double-skin chimneys, In: Proc. Int. Conf. Steel Structures of the 2000’s, 257-262, Istanbul Techn. University, 2000.

[9] Noakowski, P., Harling, A., Rost, M., Sanierung von Schornsteinen mit Stahlrohren – Grundlagen für die Bemessung und Durchbildung, Bauingenieur 77 (2000), 43-49.

[10] Schmidt, H., Hautala, K.T., Beulstabilität axialgedrückter Kreiszylinderschalen aus austenitischen nichtrostenden Stählen bei normalen und erhöhten Temperaturen, Bauingenieur, 76, 2001, 464-473.