Numerical flue gas flow analysis in wet limestone Flue Gas Desulfurization installation using Computational Fluid Dynamics

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Abstract

The main task of the Thesis was to numerically analyze the flue gas flow in wet limestone FGD installation in a CHP plant using CFD. The evaluation provided static pressure and velocity distributions across the installation and indicated the locations with increased pressure levels. The results enabled the programmable main ID fans setup to generate sufficient sub-pressure for the flue gas ducts and the collector in order for the installation to work under negative pressure. The wide range of steam boiler capacities configurations has been analyzed. The Thesis uses such engineering tools as ANSYS Fluent, ANSYS Meshing, ANSYS SpaceClaim and Engineering Equation Software. The model inputs rely on gathered internal company measurement data and records. The mesh sensitivity analysis has been conducted to maximize the results accuracy.

Keywords: *desulphurization, CFD, wet limestone FGD*

1. Introduction

The Thesis aims to obtain a numerical solution to a Navier-Stokes equations based on conservation of mass and momentum in an existing wet limestone FGD installation. The objective is to solve the problem numerically and obtain fluid static pressure and velocity distributions throughout the ducts system, that directs the flue gases to the absorber, where the wet limestone FGD process takes place. It is necessary to maintain a sub-pressure in the ducts. However the ID fans warranty measurements indicated elevated (positive) pressure levels. Hence, it was necessary to find pressure distribution and velocity of the flue gases flowing through the ducts to evaluate the existing designed ducts configuration and nominal operating parameters of the secondary Induced Draft fans, that are responsible for maintaining appropriate pressure level in examined part of the wet limestone FGD installation. The CHP plant has capacity of generating approximately 260MW$_e$ of electrical power and 810MW$_t$ of thermal power. The CHP power plant has three steam and two water boilers. The latter two work only few days a year, hence their influence on overall flue gas ducts system is negligible in regard to a whole year. Thus, the flue gas ducts of the water boilers has been omitted in the numerical model analysis. The collector is the place where the flue gas streams of each of the steam boilers (namely K1, K2, K3) flow through. Flue gas streams leave each of the steam boilers through two separate ducts per each unit. The ducts then connect and the stream flows further to the collector. Subsequently, the collector directs the streams from all three units to the absorber. The whole process and the installation is depicted in detail on Figure 1.1 and 1.2. It is worth to mention that in this case there two types of Induced Draft fans distinguished. The primary Induced draft fans are responsible to force the flue gas stream from the boilers to the ducts and collector configuration. However, secondary Induced Draft fans suck the flue gas from the collector and force the stream to flow to the absorber. The usage of Induced Draft fans results in creating negative pressure upstream and positive pressure downstream the fans. Hence, the location of the most elevated pressure was expected to occur at the inlets of the primary Induced Draft fans. The Sulphur content in the fuel (bituminous coal) ranges from approximately 0.45% to 1.2%.The power plant generates nominally 1 115 000 m_n/h of flue gases. The type of analyzed FGD system in the cogeneration power plant is wet scrubbing with limestone as a sorbent – having about 94% of SO_2 removal efficiency. The end-product of the desulphurization is gypsum. In the CHP plant after implementation of wet limestone FGD installation the flue gases ducts configuration has changed. Before the changes boilers K1, K2 and K3 has been connected to the same chimney. Figure 1.1 shows present configuration of the ducts (including ducts of hot water boilers) and collector, as well the previous flue gas ducts configuration featuring chimney, to where the flue gases were directed before the wet FGD system has been built. Presently, the flue gases from steam boilers (units K1, K2 and K3) are directed through the collector to the absorber. To ensure balanced draft in the boiler and avoid pressurization primary ID fans forces the flue gases to flow towards the collector. Each of the unit has two primary ID fans. Unit K1 has 0WS1 and 0WS2 primary ID fans, K2 has 1WS1 and 2WS2, consequently unit K3 has 2WS1 and 2WS2 primary ID fans.Currently, the flue gases are directed through wet FGD collector. Downstream the collector, secondary Induced Draft fans (ID fans), that are responsible for maintaining appropriate sub-pressure in the ducts and collector. Presently, irregular flue gas flow has been observed in individual flue gas ducts downstream the primary induced draft fans of units K1 and K2. Additionally, the data analysis obtained from warranty measurement readings for units K1, K2 and K3 has indicated overpressure occurrence on the outlets of primary induced draft fans for every working configuration conditions, for which the measurements were conducted. The resulting pressure drop influences proper operational conditions of the installation, decreasing overall performance. The vibration measurements of the ducts has further indicated increased values of vibrations levels that could lead to damage of the flue gas ducts. The high vibration level readings could be related to elevated static pressure of flue gas stream throughout the system. The thesis tackles the problem by developing a numerical model, that allows to investigate the issue source by simulating the real conditions of the wet FGD collector and in wide spectrum of operational configurations for the units K1, K2, K3. The flue gas flow analysis provides static pressure and stream velocity distribution throughout the wet FGD installation to evaluate existing design and operational parameters of the installation. The flue gas flow analysis is developed by applying CFD using the ANSYS Fluent software. The model geometry has been made based on post-completion documentation of the wet limestone FGD installation. To determine pressure levels and mass flow rates on the outlets from primary induced draft fans of units K1, K2 and K3, data from different owner-internal sources has been analyzed, such as reports, warranty measurements of induced draft fans of units K1, K2 and K3, as well as other historical records gathered throughout the installation lifespan.

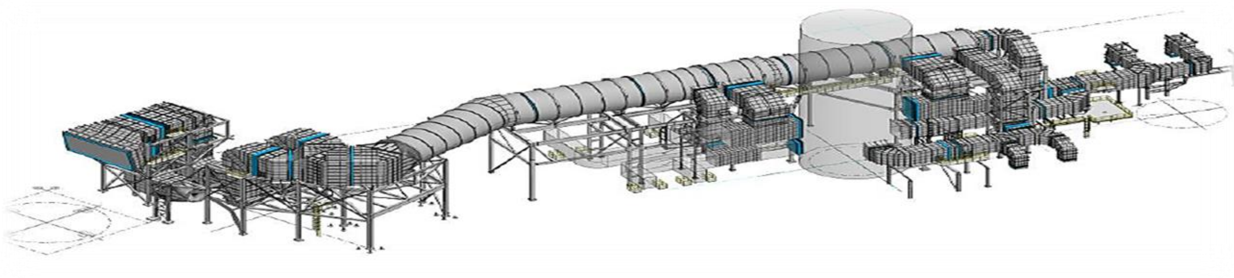

Fig. 1.1 Ducts and collector configuration of examined Wet FGD installation

Downstream the collector, main (or secondary) ID fans, that are responsible for maintaining appropriate negative pressure in the ducts and collector. Slight negative pressure in the ducts is necessary for safe operation to prevent pressurization of the boiler, flue gas collector and corresponding ducts. There are two main ID fans, labeled WWS1 and WWS2. Downstream the secondary ID fans flue gas stream inlets the absorber. Figure 1.2 reflects operational idea of wet limestone FGD system, indicating the locations of primary and secondary ID fans and showing simplified flue gas flow diagram, as well as control system responsible for managing main ID fans, that regulate the static pressure level in the collector. The control system is designed to maintain constant fixed sub-pressure level (-350 Pa changed from previous -250) in the measurement point. The pressure control point is installed on the collector, downstream the flue gas stream inlet from unit K1 and upstream the inlet of flue gases coming from unit K2. The information about static pressure level is sent from the measurement point to the controller. If the static pressure level is not equal to the designed static pressure level, the controller sends the control signal to main ID fans adjusting their rotational speed. Subsequently, main ID fans generate appropriate static pressure in particular flue gas ducts and the collector such that negative pressure in measurement point is equal to nominal designed value. One of the tasks of conducting the numerical flue gas flow analysis of examined wet limestone FGD installation is to determine the value of static pressure in the control point such that the flue gas ducts and the collector operates under negative pressure.

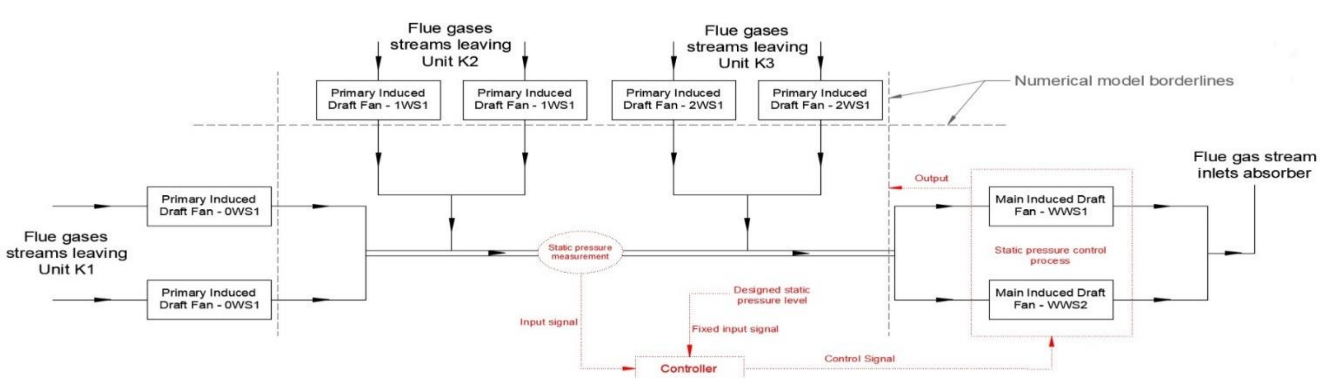

Fig. 1.2 The FGD installation operational scheme

2. Numerical model development

It was necessary to create the 3D model from detailed design documentation, including technical drawings. It was severely important to create the model very close to the real design to cover influence of all geometry details on the flue gas flow. After development of the model geometry in SpaceClaim, the numerical mesh has been created in ASNYS Meshing software to allow further progress in the numerical modeling. The mesh optimization process has been conducted, including mesh sensitivity analysis. It has allowed to create model that would provide results with satisfactory accuracy with simultaneous minimization of the computing time. In order to input appropriate boundary conditions, turbulence model and set up proper flue gas parameters, the data from Induced Draft fans warranty measurements and other existing company-internal records of operational conditions has been analyzed. The simulations has been carried out for 36 different operation conditions (steam boiler capacities), with additional 12 with repeated steam boiler capacities, but assumed averaged mass flow rates (sum of the mass flow rates of the streams leaving given unit divided by the amount of fluid inlets of respective units) to examine the influence of the regular flow in each of the channels of particular K1, K2 and K3 units. The numerical mesh optimization has been conducted in order to minimize computation time and simultaneously maintain satisfactory results accuracy. To realize the optimization process, the mesh sensitivity analysis has been performed, as well as optimization of local mesh structures and mesh densities in places with inferior quality. The mesh sensitivity is a basic iterative process of optimization of model mesh density in order to obtain results with sufficient accuracy with simultaneous minimum number of cells. The numerical model had to be solved for relatively different number of cells (various mesh densities), starting with mesh with low number of cells – in this case approximately 67k - and for subsequently increased total number of cells – here 354k, 731k and 916k consequently. The values used to indicate the subsequent accuracy improvement accompanying consequent increased mesh densities were area averaged static pressure levels at evaluation faces placed normal to the flow direction.

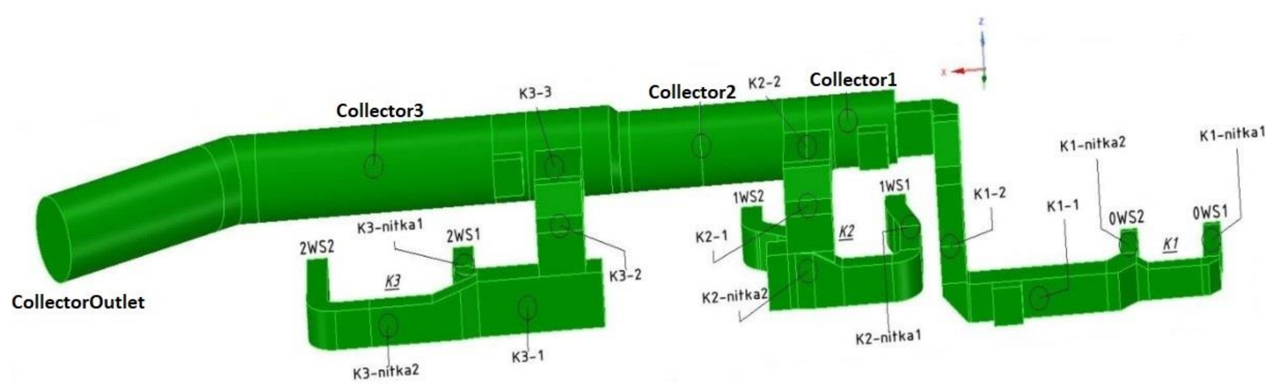

Fig. 2.1 Evaluation planes used to calculate area averaged static pressure levels at marked faces normal to the flow direction

Quality optimization has been carried out to optimize locations with lower mesh quality indicated by ANSYS Meshing software (skewness and orthogonal quality criterions) by changing the meshing method, increasing mesh densities in impactful areas and decreasing number of cells values in less impactful areas. The fourth iteration of mesh sensitivity study with about 713 thousands of number of cells has demonstrated overall error compared to iteration fifth with 916 thousands of number of cells at level 4.94%. The relative accuracy has been considered as sufficient, but the further optimization of mesh quality from forth iteration has been conducted. This resulted in an additional numerical mesh with improved quality that counts approximately 639 thousands of number of cells and have overall relative error compared to fifth iteration mesh at level 3.72%. The overall relative error has been calculated as a sum of the respective absolute errors concerned with area averaged static pressure levels differences between a particular iteration and fifth iteration (final) in respect to the final iteration. To realize comparison of final numerical mesh to other analyzed meshes the following parameter is being introduced: $h_i = 1/\sqrt[3]{N_{i,C}}$, where $N_{i,c}$ is number of cells in mesh sensitivity iteration i. Another important parameter to consider when developing a numerical mesh is expected boundary layer shape and its influence on the results. It is connected with the choice of particular turbulent model and an appropriate wall function, as well as the proper type and sufficient mesh density of near wall regions of the model. The essential parameter is often a dimensionless wall distance y^+ [1], which is equal several thousand for the analyzed problem. According to ASNYS Fluent Theory Guide from 2015, for very high Reynolds number values (analyzed case: $1{,}15 \cdot 10^6 < Re < 1{,}7 \cdot 10^6$), it can reach values as high as several thousand [2]. The Reynolds number is calculated based on measured values for respective inlets and listed in the Table 2.2.

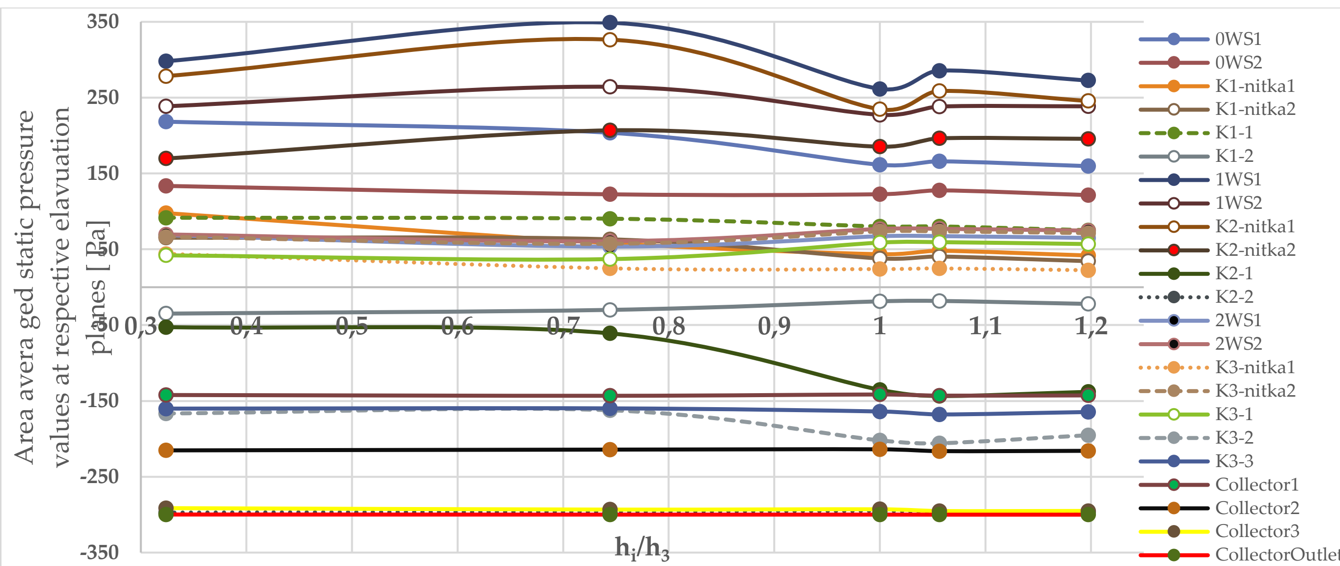

Fig. 2.2 Mesh sensitivity analysis and mesh quality optimization influence on results accuracy

In order to determine the operational parameters of the wet FGD collector the installation owner's internal report featuring primary induced draft fan measurements installed next to the steam boiler units has been analyzed. The recorded data has allowed the determination of approximate flue gas composition, density, as well as mass flow rates on the outlets from the primary ID fans of each unit for most of the steam boiler capacities configurations. In initial phase of the model development process the data regarding measured static pressure allowed to verify the accuracy of the model. Knowing the approximate flue gas composition and the temperature (see Table 2.1), the density and dynamic viscosity has been calculated using Engineering Equation Solver software.

Table 2.1 Assumed flue gas composition and parameters

Assumed flue gas composition, %					Flue gas parameters		
O_2	CO_2	N_2	H_2O	SO_2	Temperature, °C	Dynamic viscosity, kg//m/s	Density, kg/m^3
6.5	12.8	74.36	6,3	0,04	135	2.19E-05	0.8758

It is necessary to indicate the dimensions of ducts in places of respective inlets from primary ID fans. It is concerned with particular boundary conditions applied to improve the necessary inputs for computations and the initial inputs of the realizable k-ε model (turbulence model applied) [1-5]. It is concerned with turbulence intensity (assumed as 10% due to primary ID fans work impact on the fluid flow) and characteristic dimension of the respective inlet/outlet ducts. The Table 2.2 contains mentioned information and calculated hydraulic diameter, as well as other essential information to provide sufficient boundary conditions and initial values. The applied turbulence model is realizable k-ε model. The standard wall function was applied. The gravitational acceleration was assumed to be equal to 9.81 m/s^2. The solution method was second order upwind.

Table 2.2 Boundary conditions applied for consecutive inlet faces and calculated Re number for appropriate inlet conditions

Unit	**K1**		**K2**		**K3**	
Inlet from primary ID fan	**0WS1**	**0WS2**	**1WS1**	**1WS2**	**2WS1**	**2WS2**
Inlet dimensions, m	1,6	1,72	2	3,15	2	3,15
Turbulent intensity	10%		10%		10%	
Hydraulic diameter, m	1,66		2,45		2,45	
Mass flow rate, kg/s	61,47	47,69	111,67	107,82	97,78	97,16
Reynolds number	1480867	1148774	1734284	1674491	1518566	1508937

3. Numerical flue gas flow analysis

The Table 3.1 presents configuration A with maximal steam boiler capacities of each of unit K1, K2 and K2. The number one next to the letter informs that the configuration was conducted for the measured conditions. However, number 2 is a configuration, where the mass flow rate boundary conditions on the inlets from respective unit has been assumed as an arithmetic average from measured values, so that the impact of regular flow distribution for each of the two inlet ducts could be examined.

Table 3.1 The steam boiler capacities of each unit per a configuration and applied mass flow rates as boundary conditions

	Unit	K1		K2		K3	
	Steam boiler capacity, t/h	230		430		430	
	Primary Induced Draft Fan	0WS1	0WS2	1WS1	1WS2	2WS1	2WS2
A1	Flue gas mass flow rate, kg/s	53,8	41,8	97,8	94,4	85,6	85,1
A2	Flue gas mass flow rate, kg/s	47,8	47,8	96,1	96,1	85,4	85,4

The numerical model has been designed so that the static pressure levels at Control Point and at the inlets from primary Induced Draft fans are directly influenced by changes in the values of static pressure in the outlet surface

(CollectorOutlet evaluation plane). Owing to automated character of regulation system of secondary Induced Draft fans, which is based on the value of static pressure in the measurement point (Control Point), it is possible to find the static pressure level at Control Point so that in the flue gas ducts and collector a negative pressure is being maintained. The table 3.1 demonstrates the steam boiler capacities of each unit per a configuration and applied mass flow rates as boundary conditions. Not only this information is contained, but also the values of measured temperature levels on the inlets from primary Induced Draft fans. The assumed temperature of flue gases has been calculated as weighted average of the measured temperature values from the configuration A1. The respective weights are the ratios of a given mass flow rates at a inlet to a sum of all mass flow rates. The calculated temperature has been assumed as $135°C$.

The table 3.2 shows the results juxtaposition for configuration A1 and A2. The results are presented for faces, that are equivalent to inlets from respective primary ID fans. The mentioned locations have always showed the largest static pressure levels, since they are placed the furthest in the model from the secondary ID fans, that's main task is to maintain negative pressure throughout the collector and flue gas ducts. The primary ID fans generate negative pressure upstream, but also produce an increased pressure levels downstream these fans. As a result the area averaged static pressure at those locations are the highest. Therefore, if there is a negative pressure level at those locations it is quite accurate to assume that the throughout the rest of the flue gas ducts and collector the pressure will be smaller. According to results, in order to maintain sub-pressure in the collector and the ducts, it is necessary to keep the static pressure in the control point at maximum -450 Pa.

Table 3.2 Analysis results juxtaposition including calculated and measured static pressure values for each of the analyzed configuration

Analysis		K1				K2				K3				Pressure Measurement	Outlet BC
		0WS1		0WS2		1WS1		1WS2		2WS1		2WS2			
		Mass flow rate, kg/s	Static Pressure, Pa	Mass flow rate, kg/s	Static Pressure, Pa	Mass flow rate, kg/s	Static Pressure, Pa	Mass flow rate, kg/s	Static Pressure, Pa	Mass flow rate, kg/s	Static Pressure, Pa	Mass flow rate, kg/s	Static Pressure, Pa	Static Pressure, Pa	Static Pressure, Pa
A	1	**54**	171	**42**	132	**98**	294	**94**	255	**86**	35	**85**	90	-142	-300
			79		39		196		157		-60		-6	-240	-400
			-21		-61		95		57		-160		-106	-340	-500
			-122		-161		-5		-43		-260		-206	-440	-600
	2	**48**	164	**48**	132	**96**	256	**96**	220	**85**	25	**85**	78	-147	-300
			64		32		156		120		-75		-23	-247	-400
			-36		-68		56		20		-175		-123	-347	-500
			-136		-168		-44		-80		-275		-223	-447	-600

The regulation curves is a diagram that shows the area averaged static pressure levels at the inlet surfaces (the places, that demonstrate the highest static pressure levels for all steam boiler capacity configurations of each of the unit ducts) dependency on the area averaged static pressure level in control point for respective configurations. From the maintenance point of view it is extremely useful as it allows to adjust the secondary ID fans setup to produce sufficient negative pressure to ensure, that the ducts and collector system work under sub-pressure (i.e. to program the secondary ID fans to maintain certain maximum value of static pressure at control point). The simulation results, that include analysis of various configurations (variants) have allowed to develop the regulation curves, that represents the dependency of the pressure level at Control Point on the area averaged static pressure levels at the inlets from respective primary induced draft fans from units K1, K2 and K3. The results imply that the previous designed value of the static pressure at control point (-250 Pa) was incorrect as it was impossible to maintain the sub-pressure at the inlets form respective primary Induced Draft fans of each unit with this assumption. However, in order for the flue gas ducts and collector to work under negative pressure for every variant the pressure level at control point has to be kept at level -450 Pa. This value has to be treated as a maximum limit. For the pressure values at the inlets from primary ID fans ranging from -50 Pa up to -150 Pa, other comparable system has demonstrated that the installation works correctly. The comparison of variants A1 and A2 has shown the impact of irregular mass flow rates at the inlets to respective ducts of each unit. In case of regular flow, at the highest - the decrease in the static pressure levels has been observed in the inlets from primary ID fans of respective unit ducts to obtain 40 Pa in comparison to irregular flow. The mentioned highest difference has been noted for ducts of unit K2. However, the differences in other locations are negligible. Except from the inlets, the highest values of static pressure are observed to occur for ducts of unit K2 in place, where respective flue gas ducts of unit K2 joint.

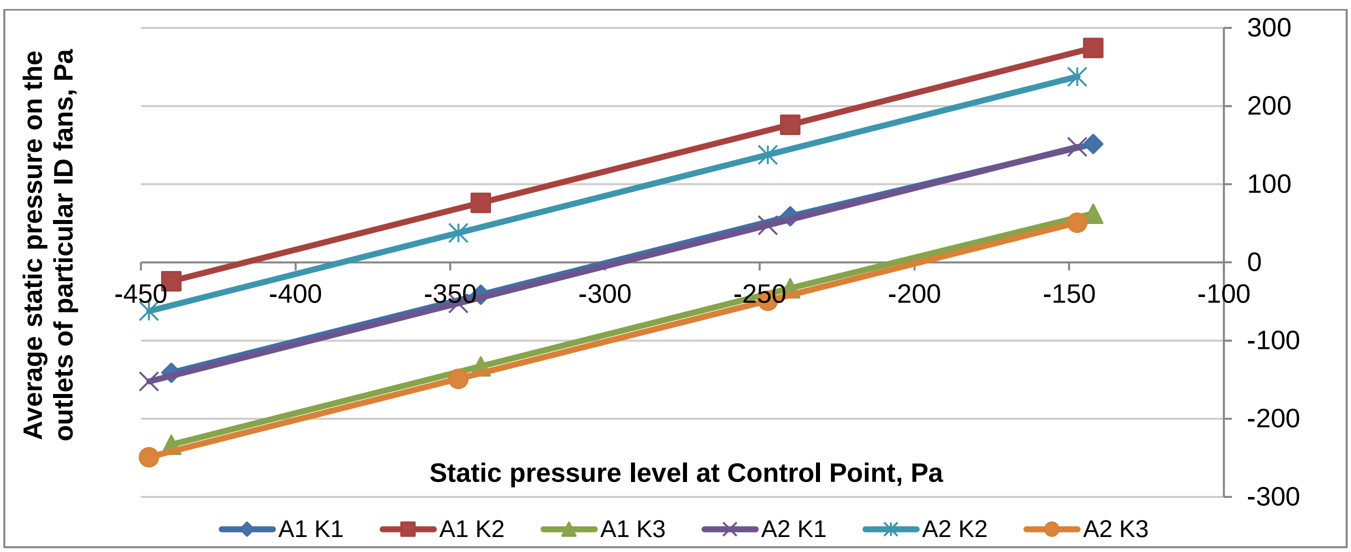

Fig. 3.1 Regulation curves for A1 and A2 configurations

The configurations A1 and A2 reflects the work of the system with maximum flue gas flow load, as it concerns the maximum steam boiler capacities for each unit. Thus, the configuration is the most important from the point of view of operation and maintenance. The static pressure distributions has indicated graduate decrease in static pressure levels throughout the installation for consecutive assumed static pressure levels (i.e. -300; -400; -500 and -600 Pa) at “CollectorOutlet” surface as “pressure-outlet” boundary condition. The highest values of static pressure has been observed to be in K2 unit ducts and to a considerably lesser extend in K1 unit ducts. The velocity streamlines is a group of curves being instantaneously tangent to the velocity vector of the flow. Therefore, they present the direction in which a fluid element at given point will travel. The resulting velocity streamlines has allowed to visualize this for the analyzed wet limestone FGD installation. The highest velocities has been noticed on K2 unit ducts. By plotting static pressure distribution with an indicative red-colored positive pressure levels in the installation the visualization of the places that work incorrectly (locations, where there is a positive static pressure levels) has been enabled. The highest pressure drop has been observed to occur in K2 unit ducts. The positive static pressure occurs for whole length of respective K2 ducts for every variation calculated that included the work of unit K2.

BC $p = -600\ Pa$ at ColelctorOutlet for A1(left) and A2(right) respectively

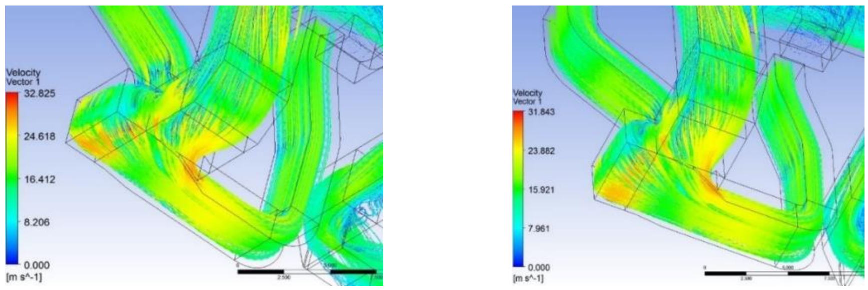

Fig. 3.2 Velocity streamlines of K2 unit ducts overview for A1 and A2 profiles with outlet BC -600Pa

For each of the configurations, where the unit K2 is running, the velocity streamlines have very close character to the flow streamlines on Figure 3.2. The way, in which the K2 unit ducts are connected causes mutual counteracting of particular flue gas streams, simultaneously resulting in significant pressure drops and equivalently causing occurrence of positive pressures on the inlets from primary Induced Draft fans of K2 unit. It has been recommended to optimize the flow through modification of the local geometry of the duct system.

Conclusions

The evaluation provided static pressure and velocity distributions throughout the examined installation and indicated the locations subject to increased pressure levels. The different steam boiler capacity collective variants have been analyzed, providing exhaustive elaboration for an installation owner. The static pressure distributions has indicated graduate decrease in static pressure levels throughout the installation for consecutive assumed static pressure levels (i.e. -300; -400; -500 and -600 Pa) at “CollectorOutlet” surface as “pressure-outlet” boundary condition. The highest values of static pressure has been observed to be in K2 unit ducts and to a considerably lesser extend in K1 unit ducts for configurations, where the K2 unit was operating. The positive static pressure occurs for an entire length of respective K2 unit ducts for every variation calculated that included the work of unit K2. The resulting velocity streamlines has allowed the visualization of the fluid flow and local velocities of the streams for the analyzed wet limestone FGD installation. The highest velocities has been noticed on K2 unit ducts. For each of the configurations, where the unit K2 is operating, the particular velocity streamlines has showed adverse character. The manner, in which the K2 unit ducts are joint together causes mutual counteracting of respective flue gas streams, simultaneously resulting in high pressure drops and causing occurrence of positive pressures on the inlets from primary Induced Draft fans of K2 unit. Thus, the determined location with faulty duct configuration design, that potentially could be improved. It has been advised to optimize the fluid flow through modification of the local geometry of the ducts system. The numerical simulation results, that include analysis of different operational configurations have allowed the development of the regulation curves, that demonstrate the dependency of the pressure level at Control Point on the area averaged static pressure levels at the inlets from respective primary induced draft fans from units K1, K2 and K3. In order for the flue gas ducts and collector to work under sub-pressure for every variant the pressure level at control point has to be kept at level -450 Pa. This value has to be treated as a maximum limit. In other words, the system evaluation has enabled the programmable secondary Induced Draft fans setup to produce sufficiently low pressure for the flue gas ducts and the collector in order for the installation to work under negative pressure. The comparison of variants A1 and A2 has shown the impact of irregular mass flow rates at the inlets to respective ducts of each unit. In case of regular flow, the decrease in the static pressure levels has been observed in the inlets from primary ID fans of respective unit ducts to obtain at most 40 Pa in comparison to irregular flow (for the same steam boiler capacities). This highest difference has been noted for ducts of unit K2.

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