Pressure loss reduction in ventilation ducts by shape optimization of the removable profiled components

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Abstract. Reduction of pressure loss in ventilation systems can be achieved by changing the shape of the airflow region and smoothing the boundary surfaces. The installation of special profiling components inside a straight shaped part of ventilation duct is the simplest way to reduce the coefficient of local resistance and pressure loss. For the best result under given conditions, the shape optimization problem must be formulated and solved. In this paper, we use the open source code software and numerical methods to study the optimal-shaped drag reduction components in elbow ventilation ducts. Computational Fluid Dynamics is used to predict the flow fields and the drag reduction effect. After the validation of flow model against existing experimental results, a detailed study has been conducted to shape optimization of removable profiled components. The optimization problem is parameterized by a small number of structural variables, which are the coordinates of the control points of the splines that form the contours of the flow region. Total pressure loss coefficient is selected as the objective function for optimization. A genetic algorithm is used as an optimization method. The results reveal that the removable profiled drag reduction component can reduce the resistance in ducts by 60%–80%.

Keywords: ventilation duct, pressure loss, computational fluid dynamics, OpenFOAM, shape optimization, genetic algorithm.

1 Introduction

Reduction of pressure loss is one of the important tasks of ventilation systems maintenance, improving energy utilization, saving energy, and reducing emissions.

Extensive experimental and numerical works have been directed to investigation on the accuracy of using CFD for pressure loss prediction in duct fittings and the factors affecting its accuracy [1–9]. It was found that the combination of the k-ε model and the higher order discrete numerical scheme produced the highest accuracy (with a relative error of 10%).

A number of studies have been conducted to understand the local pressure loss in ducts and pipes and optimize the novel and existing system components [10-13]. Pressure losses in ducts are associated with local resistances in disturbing elements such as bends, branches, fittings due to the adjustment and deformation of the flow, formation of vortex flows when the flow stalls from the sharp edges of the structure, occurrence of circulation zones, surface roughness. In ventilation systems, local drag generally accounts for 40 % of the total drag losses. It is possible to reduce aerodynamic drag and pressure loss by changing the shape of the air flow region, by smoothing the bounding surfaces, profiling the channel walls according to the outlines of the circulation zones, determined by numerical or analytical methods.

The installation of wedge-shaped drag reduction component with suitable height [14], guide vanes [15–16] or special profiling components [17–20] can reduce the coefficient of local resistance by suppressing the circumfluence and reducing the energy dissipation, keeping the dimensions of the part minimal. The outlines of such a profiling component should completely repeat the outlines of the free streamline dividing the region of the main flow in the channel and the vortex zone formed behind the
sharp perturbing element. This approach allows improving the aerodynamic properties of the system, but in order to achieve the best result under given conditions, the optimization problem must be formulated and solved.

In this paper, the drag reduction effect influenced by the optimal-shaped removable components in 90° elbow ventilation ducts is investigated with the help of numerical methods.

2 Materials and methods

We use the open source code software and computer simulation by numerical methods to study the optimal-shaped drag reduction components in 90° elbow ventilation ducts. The drag reduction approach employed here is putting removable components in the inner side of the elbow wall where vortices existed to change the flow structure and suppress the generation and development of the circumfluence.

2.1 Computational Fluid Dynamics approach

Computational Fluid Dynamics (CFD) is employed to predict the flow pattern and the drag reduction effect.

Software. OpenFOAM was applied as CFD software in the present work. OpenFOAM (Open Source Field Operation And Manipulation) is a freely distributed toolkit for computational fluid dynamics based on the finite volume method [21–24].

Model geometry and mesh. The present work focuses on a 90° bend elbow ducts. The blockMesh utility of OpenFOAM was used as a grid generator to create regular grids formed by a combination of hexagonal blocks. The grids used in simulation are non-uniform and are denser near the walls and the drag reduction components where the velocity gradients are expected to be larger (Figure 1). Grid generation is fully parameterized. The channel dimensions, the coordinates of some control points, the number and proportions of cell sizes are used as parameters. Grid refinement and number of cells are determined after model validation study. Coarse grids are mainly used in the present work.

Figure 2 presents a schematic representation of the duct geometry and the key geometrical parameters used in the fluid simulations. Flow enters a straight section at the upper left corner of the figure. The (x, y) coordinates are in the plane of the paper, with the origin centered at the end of inlet straight section.

![Figure 1. Model mesh sample and grid refinement scheme](image1.png)

**Figure 1.** Model mesh sample and grid refinement scheme.

![Figure 2. Model geometry and the key geometrical parameters](image2.png)

**Figure 2.** Model geometry and the key geometrical parameters.

Flow model. The problem is considered as the steady single phase turbulent flow of a viscous, incompressible and isothermal fluid, with the working fluid being air. Gravitational effects and physical properties change are ignored. Two-dimensional Reynolds Averaged Navier–Stokes (RANS) equations are solved by finite volume method using the implicit steady-state solver simpleFoam and...
turbulence treatment with the standard $k-\varepsilon$ model. Near wall treatment of flow is based on the wall functions. The second order bounded Gauss linear upwind discrete scheme is used for calculating the equations, with a pressure velocity coupling is achieved using SIMPLE algorithm. The default under relaxation factors (0.3 for pressure and 0.7 for others) were used to aid convergence. Mean duct velocity is fixed at the inlet boundary location. Zero gradients and zero background pressure are specified at the outlet boundary.

**Local pressure loss estimation.** The local pressure loss coefficient and the drag reduction rate are used in the comparison of drag reduction effects.

The total pressure loss of the ventilation duct is the difference between total pressure values at inlet ($p_0$) and outlet ($p_3$) parts and is equal to sum of the friction and local pressure loss:

$$\Delta p = p_0 - p_3 = \Delta p_f + \Delta p_c \quad (1)$$

The friction pressure loss depends on the lengths of duct straight sections

$$\Delta p_f = \sqrt{\nabla p_u} d_u + \sqrt{\nabla p_w} d_w \quad (2)$$

where, $\nabla p$ are the estimations of total pressure gradients at inlet and outlet straight parts of duct at sections 0, 1, 2, 3 with fully developed flow

$$\nabla p_u = \frac{p_3 - p_1}{y_3 - y_1}, \quad \nabla p_w = \frac{p_2 - p_0}{y_2 - y_0}, \quad d_u = x_u + w_u / 2, \quad d_w = y_u + w_u / 2 \quad (3),(4)$$

The local pressure loss is equal to a multiple of the dynamic pressure and local pressure loss coefficient $\zeta$

$$\Delta p_c = \frac{\zeta p u^2}{2}, \quad (5)$$

where, $u$ is average flow velocity, $\rho$ - fluid density.

After substitution of Eq. (1) for Eq. (4) the local pressure loss coefficient can be determined as

$$\zeta = \frac{2(\Delta p - \Delta p_f)}{p u^2}, \quad (6)$$

Drag reduction rate is given by

$$R = \frac{\zeta - \zeta_0}{\zeta_0} \cdot 100\%, \quad (7)$$

where, $\zeta$ and $\zeta_0$ are the local pressure loss coefficients of the duct with and without drag reduction components.

Local pressure loss coefficient is calculated by means user application created in OpenFOAM software.

2.2 Optimization method

Computational design optimization is employed to predict the shape of removable drag reduction components in elbow ventilation ducts.

**Software.** DAKOTA was applied as design optimization software in the present work. DAKOTA (Design Analysis Kit for Optimization and Terascale Applications) is freely distributed tool with an open source code for the numerical solution of design optimization problems. DAKOTA provides a universal interface for interacting with applications and allows solving many different design problems [25–26].

The optimization problem is parameterized by a small number (2–5) of design variables, which are the coordinates of the control points of the splines that form the contours of the flow region. Total pressure loss coefficient is selected as the objective function for optimization. The parametric optimization problem is solved in the DAKOTA program, which controls the process of determining the velocity and pressure fields in OpenFOAM by automatically modifying text files that specify the parameters of the grid generator.
Genetic algorithm. A genetic algorithm is used as an optimization method. The genetic algorithm is a heuristic population-based search engine optimization method that models adaptation mechanisms similar to natural selection in wildlife. The implementation of the genetic algorithm is as follows:

1. Genotype formulation. Structural variables are encoded in binary strings, the length of which is determined by the range of permissible parameter values and the required accuracy (20-bit string provides a representation error of $10^{-6}$), and then combined to form a "genotype". Each variant of the genotype represents a possible solution to the problem and is treated as inheritable characteristics of an individual.

2. The fitness function formulation. The objective function of the optimization problem, which depends on the parameters and, therefore, on the genotype, is interpreted as a function of an individual’s fitness for living conditions.

3. Population formation. A predetermined number (population size, usually from several tens to several hundreds) of "individuals" of the population is generated, with genotypes randomly formed.

4. Selection. The fitness function is calculated for all individuals in the population. Values are ranked. Half of the individuals with the worst values of the fitness function are removed from the population ("dying out").

5. Crossover. Pairs of "parents" giving birth to two "descendants" are randomly formed from the remaining individuals with a given probability (crossover rate). Descendants inherit the parental genotypes as a result of the action of the binary crossing operator. A bit is randomly selected in the genotypes of the parents, dividing them into two parts. Parts of genotypes taken from different parents are stored in descendants.

6. Mutations. The descendants' genotypes change randomly as a result of the action of the binary mutation operator. Individual bits are inverted with a given low probability (mutation rate). Mutations prevent the effect of "cloning", that is, the predominance of individuals with the same genotypes and the termination of the evolution process.

7. Generation. Parents and their descendants form a new generation of the population. The selection, crossing and mutation processes are repeated until the specified criteria are achieved.

8. Completion criteria. The optimization process by the genetic algorithm stops when finding the extreme value of the fitness function with a given accuracy or reaching a given number of generations (descendants). The solution to the problem is a set of parameters corresponding to the genotype of the individual with the best value of the fitness function.

The framework DAKOTA–OpenFOAM executes simulations in parallel mode.

2.3 Numerical simulation details
The shape optimization problem for the removable profiled components of the ventilation duct was solved using the OpenFOAM 3.0 and DAKOTA 6.6 programs compiled from source codes in the Ubuntu 14.04 operating system [27].

CFD parameters:
- inlet size $w_i = 0.1$ m; outlet size $w_o = 0.06$, 0.1, 0.2 m;
- inlet part length $L_1 = 8$ m; outlet part length $L_2 = 16$ m;
- density $\rho = 1.204$ kg/m$^3$ and viscosity $\nu = 1.516 \times 10^{-5}$ m$^2$/s;
- inlet velocity $u = 10$ m/s;
- Reynolds number is about $1 \cdot 10^4$.

Optimization parameters:
- design variables: 5;
- function evaluations: 200;
- number of generations: 100;
- population size: 20;
- crossover rate: 0.8;
- mutation rate: 0.1;
simulations in parallel

4. Results and discussions

A model validation study was performed for several cases of grids with different values of the $y^+$ parameter at walls and CFD results were compared with generally accepted published experimental data [28].

As observed from the Figure 3, there are minimal differences between the predicted results and experimental data for grids with the average values $y^+$ in range $30 < y^+ < 300$. But there is a noticeable disagreement (10-20%) between the experimental results and CFD predictions.

In order to improve the accuracy of CFD simulations an auxiliary optimization study using the DAKOTA–OpenFOAM framework was performed to find a modified set of closure coefficients of the $k-\varepsilon$ turbulence model. The default values of the closure coefficients for the $k-\varepsilon$ turbulence model are $C_\mu = 0.09$, $C_\epsilon = 1.44$, $C_{\sigma_1} = 1.92$, $\sigma_1 = 1$, $\sigma_2 = 1.3$. The modified values based on the optimization method were found to be $1.4 < C_\mu < 1.5$, $1.4 < C_{\sigma_1} < 1.44$, $2.7 < C_{\sigma_2} < 3$, $0.27 < \sigma_2 < 0.9$. The modified CFD model showed higher agreement with experimental data with error less than 5%.

![Figure 3](image)

**Figure 3.** Dependence of predicted local pressure loss coefficients $\zeta$ of 90° elbow ducts on wall value $y^+$ and outlet/inlet size relation $w_1/w_0$. Dashed lines represent results with modified turbulence model. $\zeta$ – experimental data [28].

After the validation of present model against existing experimental results, a detailed study has been conducted. During simulations the near-wall meshes are refined to achieve the desired wall values $y^+ > 30$.

Simulation results (Figure 4) show that the removable drag reduction component with suitable shape can reduce the resistance in elbow by suppressing the circumfluence and accelerating uniform flow formation. In fact, installation of a profiled component changes the ventilation duct with a sharp corner into the channel with a smothed corner.
Figure 4. Simulation results of velocity flow fields for cases with and without optimal-shaped removable components and different outlet/inlet size relation.

Optimal shapes of removable profiled drag reduction components for ducts with different outlet/inlet size relation (0.6, 1.0, 2.0) were obtained (Figure 5). The shapes of a profiling components repeat the outlines of vortex zones formed behind the sharp corners according to [19], but for the frontal part only. The tail parts of the components work as diffusers, but their influence on the resistance coefficients is less significant.

Figure 5. Optimal shapes of removable profiled components for cases with different outlet/inlet size relation and the shape of component as vortex zone outline according to [19].

The removable profiled drag reduction components with optimized shapes significantly decrease (up to 5 times) the pressure loss coefficients of an elbow duct, providing a drag reduction rate of 60%–80% (Table 1). The pressure loss coefficients values of an elbow ducts tends to values of a rounded elbow ducts [28]. Comparison with the results recalculated in OpenFOAM according to the method described in [19] shows that despite the differences in the obtained shapes of the profiled components, the values of the pressure loss coefficients differ slightly.
Table 1. Pressure loss coefficients and drag reduction rate for ducts with different outlet/inlet size relation.

| outlet/inlet size relation | experimental | simulation results | simulation results for cases with optimal-shaped removable components | Drag reduction rate |
|---------------------------|--------------|--------------------|---------------------------------------------------------------------|---------------------|
| $\frac{w_1}{w_0}$ | $\zeta_0$ | $\zeta$ | $\zeta_{opt}$ | $R_\zeta$ |
| 0.6 | 1.50 | 1.57 | 0.47 | 68 % |
| 1.0 | 0.79 | 0.83 | 0.19 ($0.17^*$) | 76 % |
| 2.0 | 0.55 | 0.54 | 0.10 | 81 % |

* recalculated in OpenFOAM according to [19]

4 Conclusions

In this paper, the drag reduction effect influenced by the optimal-shaped removable components in 90° elbow ventilation ducts is investigated by means of CFD simulations coupled with a genetic algorithm.

It was determined that the use of the $k$-$\varepsilon$ turbulence model with a modified set of closure coefficients and wall function wall treatment yields predictions of pressure losses in duct systems that are within 5% of experimental data.

Optimal shapes of removable profiled drag reduction components for ducts with different outlet/inlet size relation were obtained with a drag reduction rate of 60%–80%. The frontal part shapes of profiling components repeat the outlines of vortex zones formed behind the sharp corners. The tail parts of a components work as diffusers.

The presented simulations were focused on wide 90° elbows with sharp corners only. A similar method can be used for the other ventilation fittings like transitions, diffusers, cross, branches etc. The simulation based analysis taking into account spatial effects, unsteadiness of the flows, wall roughness, advanced turbulence models will be continued in the following works.

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