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Research Paper

Web-based forecasting system for the airborne spread of livestock infectious disease using computational fluid dynamics

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Livestock infectious diseases, such as foot-and-mouth disease (FMD), cause substantial economic damage to livestock farms and their related industries. Among various causes of disease spread, airborne dispersion has previously been considered to be an important factor that could not be controlled by preventive measures to stop the spread of disease that focus on direct and indirect contact. Forecasting and predicting airborne virus spread are important to make time for developing strategies and to minimise the damage of the disease. To predict the airborne spread of the disease a modelling approach is important since field experiments using sensors are ineffective because of the rarefied concentrations of virus in the air. The simulation of airborne spread during past outbreaks required improvement both for farmers and for policy decision makers. In this study a free license computational fluid dynamics (CFD) code was used to simulate airborne virus spread. Forecasting data from the Korea Meteorological Administration (KMA) was directly connected in the developed model for real-time forecasting for 48 h in three-hourly intervals. To reduce computation time, scalar transport for airborne virus spread was simulated based on a database for the CFD computed airflow in the investigated area using representative wind conditions. The simulation results, and the weather data were then used to make a database for a web-based forecasting system that could be accessible to users.

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Nomenclature

A_{animal}	recommended rearing area (m^3 $head^{-1}$)
$C_{aerosol}$	livestock aerosol concentration by animal species, ages, and floor type (mg m^{-3})
C_{μ}	empirical constant of the turbulence model (approximately 0.09)
N_{animal}	number of animals in a livestock house (head)
$P_{infection}$	infection ratio in an infected livestock house (%)
p	constant pressure (Pa)
Q_{point}	livestock aerosol emission rate for attaching a virus (mg s^{-1}).
S_{ϕ}	source term
s	time interval for CFD simulation (s)
t	time (s)
U	velocity (m s^{-1})
u^*	fiction velocity (m s^{-1})
z_0	height of the surface roughness (m)
Γ	diffusion coefficient
δ	bound layer depth (m)
ε	turbulent dissipation rate (m^2 s^{-3})
κ	von Karman constant (0.4)
ρ	density (kg m^{-3})

Abbreviations

AWS	automatic weather station
CDMA	code division multiple access
CFD	computational fluid dynamics
DEM	digital elevation model
FMD	foot-and-mouth disease
GIS	geographical information system
PM10	particle matter under 10 μm
SAS	severe acute respiratory syndrome
SEM-EDX	scanning election microscopy energy dispersive X-ray spectroscopy
$TCID_{50}$	50% tissue culture infective dose
TIN	triangular irregular network
WDAS	weather data acquisition server
WebFoS	web-based forecasting system

1. Introduction

To increase productivity, the livestock industry is moving to mass operation systems, therefore large economic damage can occur during outbreaks of livestock infectious diseases. Since 2000, in Korea there have been four foot-and-mouth disease (FMD) outbreaks. During the 2010/11 FMD outbreak, 3.35 million pigs were slaughtered to prevent virus spread, which resulted in a decrease in animals of 32%, while the direct damages, including the costs for farm compensation and preventive measures, reached 3 billion USD and related damages, including costs to feed companies, the decrease in exports, and reduced consumer demand, reached 4 billion USD, as estimated by KREI (2011). Therefore, there is an urgent need to minimise the damage from livestock infectious diseases at the early stages of any outbreak by means of preventive measures. The outbreak of livestock infectious diseases has not be blocked because of the various transmission routes, and tracking of the spread has failed due to the difficulties in field monitoring. There are three routes by which FMD can be transmitted by livestock aerosols and surface contact to respiratory organs (Weber & Stilianakis, 2008); 1) direct contact from infected animal to healthy animals, 2) indirect contact by infected objects such as the human body, vehicles, equipment, feed, refrigerators, and 3) airborne spread through airflow. The airborne spread of livestock disease has not be considered in terms of taking preventive measures due to a lack of information. However, a comprehensive counterplan should consider not only direct and indirect contact transmissions but also airborne transmission via considering the continuously changing airflow patterns from weather conditions.

A current preventive measure that has been used to reduce FMD spread has been the use of preventive vaccinations within 3 km of infected farms or eradication of neighbouring animals within 1 km (Martínez-López, Perez & Sánchez-Vizcaíno, 2010). Geering and Lubroth (2002) suggested a disease management strategy based on; 1) denying access of the virus to susceptible host animals, 2) avoiding contact between infected and susceptible animals, 3) reducing the number of infected or potentially infected animals in livestock populations, and 4) reducing the number of susceptible animals. Most of the preventive measures used to date have focused on a blockade of direct and indirect transmission of virus regardless of the airborne transmission. Multiple factors should be considered in making preventions and forecasting, but there are a substantial number of difficulties basing this on field experiments, including a lack of basic information on virus spread, the presence of an incubation period, and having a detection problem or a delay in disease declaration.

It is difficult to measure airborne spread under ever-changing weather conditions, thus rare quantitative data are available from simulation models. Viruses that are suspended in the air exist as fine particles; there are limitations to capturing these viruses when using an air sampler and also to detect a quantitative dose of the virus under field or laboratory conditions. Modelling approaches of airborne virus spread have been developed to get over these limitations. Martínez-López et al. (2010) suggested an FMD spread model that used seven variables; (1) movement of animals, (2) local spread, (3) infectivity, (4) zones, (5) resources for depopulation, (6) movement restriction, and (7) surveillance. Stevenson et al. (2013) suggested a spatial and stochastic simulation model was developed for epidemiological investigation and considered airborne spread, animal movement, farm operating methods, incubation period, indirect contact, susceptibility, and other factors. Their model calculated the probability of infection by the distance from the infected farms via airborne spread of virus using weather information and look-up tables. However, considerable numbers of quantitative variables relied on expert opinions and required more research.

Aerodynamics models have been developed to predict the airborne spread of livestock diseases (Krumkamp et al., 2009; Mayer, Reiczigel, & Rubel, 2008; Seo et al., 2014). Among various simulation techniques, computational fluid dynamics (CFD) which solves mathematically aerodynamic problems in various research fields, has been considered. Compared to the Gaussian-based simulation models that are currently used for virus spread simulations, CFD has advantages with respect to specific airflow analysis, complex topographical information and related facilities in a local area that has a concentration of livestock farms (Hong et al., 2011; Seo et al., 2014). Because a considerable number of the livestock facilities in Korea are concentrated in hilly and mountainous areas to avoid complaints from residential areas due to livestock odours, and because there are therefore complex airflows, a CFD approach is very important for analysing airborne virus spread caused by airflow.

Although data on airborne spread during past disease outbreaks is important, the estimation and forecasting of airborne virus spread is more important to provide the time required to prepare against infection. The perception that simulation models are useful for epidemiological investigations 'after' an outbreak needs to be changed to one where combined with weather forecasting they are useful for real-time forecasting of the airborne spread 'before' an outbreak. The concept is that predicted airborne spreading data could be provided for research and public purposes by means of a user-friendly system for easy access; a system that provides web-based information would be helpful for these reasons. Such a system could play an important role in developing an effective strategy of preventive measures against the possibility of airborne livestock infectious disease based on a rapid warning system.

The objective of the work reported here was to build the main structure for a forecasting system for the airborne spread of livestock disease so as to prepare and manage the risk of airborne virus spread according to weather conditions. The main steps can be divided as follows:

1) Securing the basic information for airborne livestock virus characteristics to analyse airborne spread under weather conditions in the research area,
2) Developing a three dimensional CFD simulation model and a related analytical technique for real-time prediction,
3) Construction of a database for weather forecasting information and its precise interlock with GIS (geographical information system) information,
4) Rapid and accurate prediction of airborne livestock spread using CFD and weather forecasting information,
5) Construction of a web-based forecasting system (WebFoS) that considers user requirements and purposes.

2. Literature reviews

2.1. *Airborne spread of FMD disease*

The airborne spread of livestock disease such as FMD has been suggested for some time by many researchers groups (Seo, 2012; Tellier, 2006; Weber & Stilianakis, 2008). Airborne virus has been known to survive approximately 24–48 h in the air, and livestock aerosols generated from farms can carry livestock viruses from an infected farm (Brockmeier & Lagar., 2002; Kristensen et al., 2004; Tellier, 2006). The aerosols that are generated from pig farms are suspended on feed particles in the air and are regenerated on a floor surface (Heber, Stroik, Faubion, & Willard, 1988; Takai et al., 1998). The particle sizes of the livestock aerosols that are suspended in the air are therefore 2–3 μm (Cambra-López, Aarnink, Zhao, Calvet, & Torres, 2010); these particles can stay in the air for two days and be dispersed throughout the airflow that is affected by ventilation and weather conditions. The appropriate conditions for FMD viruses be attached to livestock aerosols are >60% relative humidity and <27° C air temperature and the survival of the virus is little influenced by the effects of strong UV radiation (Cannon & Garner, 1999). Therefore, livestock aerosols combined with FMD virus can move far away from their source, following air currents when environmental and weather conditions permit virus survival.

The emission rate of an FMD virus can be described in units of $TCID_{50}$ (50% tissue culture infectious dose), which represents a capacity of virus that infects 50% of the tissue cells. The emission rate of a livestock airborne virus increases with the size of the farm and the number of infected animals that excrete the virus; pigs excrete a large amount of viruses, approximately $10^{5.6}$–$10^{8.6}$ [$TCID_{50}$] animal^{-1} d^{-1}, which can be compared to the other ruminants, such as cows and sheep, which excrete by 10^4-10^5 [$TCID_{50}$] animal^{-1} day^{-1}. On the other hand, the amounts of critical virus concentration for infection are 10^3 $TCID_{50}$ for pigs and 10 $TCID_{50}$ for other ruminants (Alexandersen and Mowat, 2005), which shows that the FMD propagation route tends to move from windward for pig farms to leeward for dairy and sheep farms.

Gloster, Doel, Gubbins, and Paton (2008) have studied detecting airborne virus in the air from 20 FMD infected pigs. A peak concentration of FMD virus was detected two days later from an initial excretion of airborne virus. Doel, Gloster, and Valarcher (2009) and Ha et al. (2012) screened instruments for their effectiveness at sampling airborne viruses when using FMD virus and PRRS (porcine reproductive and respiratory syndrome) virus respectively; both sets of results showed that bio-samplers (SKE biosampler, SKC Inc., Pennsylvania, USA) and potable air samplers (PCXR8, SKC Inc., Pennsylvania, USA) were effective at capturing airborne virus. However, these results were not directly relevant to applications at field situations during and outbreak because the experiments were conducted in restricted and controlled small spaces using relatively high virus concentrations compared to virus concentrations found in the air from infected farms. Brockmeier and Lager (2002) and Kristensen et al. (2004) conducted field experiments for airborne virus spread using animals, and various measurement techniques suggested by international organisations and research groups such as WHO (2006), Nicoll (2006), Aledort, Lurie, Wasserman, and Bozzette (2007), and Sagripanti and Lytle (2007). Li et al. (2007) and Gao, Niu, Perino, and Heiselberg (2009) attempted to discover a mechanism for airborne virus spread by using tracer gases. However, field and laboratory experiments still have limitations due to point measurements, unstable weather conditions, low virus concentrations in the air, and complex detection techniques.

2.2. Modelling approaches for airborne spread

Aerodynamic modelling for the prediction of airborne livestock virus spread has attempted to overcome the limitations of field experiments. Gaussian based dispersion models were initially used for aerosol modelling and they have been updated to enhance their modelling accuracy by considering the effects of UV radiation, air temperature, virus mortality during airborne phase due to dehydration, and airborne spread (Lighthart and Mohr, 1994). The RIMPUFF (puff diffusion model developed by Risø DTU national laboratory for sustainable energy, Denmark) were also used to predict airborne FMD virus spread (Sørensen et al., 2001), and complex topographical information was the most important factor for forming virus dispersion patterns when using dispersion modelling (Mikkelsen et al., 2003). To predict airborne virus spread, the RIMPUFF model, which is a regional and large-scale dispersion model, was used with a virus production model (VPM) (Mikkelsen et al., 1997; Thykier-Nielsen et al., 1993). Other cases have been analysed regional aerodynamic dispersion by simulating complex airflow patterns through hills and mountainous regions while considering land utilisation characteristics (Astrup, Jensen, & Mikkelsen, 1997; Mikkelsen et al., 1997). Gloster, Blackall, Sellars, and Donaldson (1981) estimated airborne FMD virus spread from infected farm as point sources by using a Gaussian plume model, and predicted an airborne spread distance of 10 km assuming 10^8 infectious units per pigs per day; over 65% of the infection was shown to be related to a particle size of <6 μm. Casal, Moreso, Planas-Cuchi, and Casal (1997) simulated airborne spread of virus using ALOHA (areal location of hazardous atmospheres, NOAA, 1992), which resulted in a 7 km dispersion distance. Donaldson, Alexandersen, Sorensen, and Mikkelsen (2001) mentioned that the airborne dispersion of FMD virus excreted by cows and sheep can be 100–200 m.

Krumkamp et al. (2009) used an effective reproduction number to estimate the SARS (severe acute respiratory syndrome) virus spread, and suggested that close contact and exposure to virus are very important for disease spread. Regional airflow patterns play an important role on airborne FMD virus spread, as suggested by Mayer et al. (2008), who used a Lagrangian-particle model. Gloster et al. (2010) gathered data from research groups among six countries to estimate airborne FMD virus spread using their own Gaussian-Lagrangian models based on the epidemiological investigation of the 1967 FMD outbreak in UK. After modelling analysis, risk factors on airborne virus spread from infected farms were divided into four stages including high-risk, mid-risk, low-risk, and no-risk.

Gaussian models assume airborne virus dispersion as an aerosol mass and analyse the approximate dispersion, but minimised the environmental factors such as complex topography, variation of wind conditions, air temperature, and relative humidity (Traulsen & Krieter, 2012). CFD can simulate airflow patterns and aerosol dispersion while considering complex topographical information and various specific environmental factors (Seo et al., 2014). The livestock farms in Korea are concentrated around hilly and mountainous area and therefore complex topographical information, surface roughness and ground utilisation needs to be considered. This is in contrast to Gaussian based models which are more easily incorporated into level terrain.

2.3. Virus emission of FMD

Aerosol concentrations generated from livestock farms alter according to multiple factors including the nature of the facility, ventilation conditions, feed, animal species, animal age, and environmental conditions; animal activity, breeding density, and air humidity conditions are also important. Haeussermann et al. (2008) suggested a dynamic model to predict the relationship between aerosol concentration and related factors using the PM_{10} (particle matter under 10 μm) concentration in pig farms by means of the ventilation rate, animal activity, feed supply method, internal air humidity, animal weight, and the other factors. Other research groups have also suggested that the aerosol concentration generated from livestock farms depends on the number of animals, the animal age, activity, the ventilation rate, the internal air temperature, the air humidity, feed types, and other factors (Gustafsson, 1999; Kim, Ko, Lee, Park, & Kim Chi, 2005; Puma & Maghirang, 2000).

As shown in Table 1, the virus emission rate from pigs was higher than for the other animal species, whilst the critical virus concentration of FMD infection for cattle was 130 times lower than that for pig. This finding indicates that pigs can emit more FMD virus into the air and that cattle can be infected via airborne FMD spread with a higher probability (Sørensen, Mackay, Jensen, & Donaldson, 2000). However, these results were established in single animal-oriented laboratory experiments, and there are few studies for addressing FMD virus emission rate at a farm scale. As stated earlier the virus can be spread in the air by attachment to aerosols in a livestock house (Cox, Aggarwal, Statham, & Barnett, 2003; Seo et al., 2014; Treanor, 2004; Wright and Webster, 2001). Using this assumption, it is possible to analyse airborne virus spread in terms of livestock aerosol dispersion using CFD techniques. The emission rate of a livestock aerosol in each livestock building was derived from a previous study conducted by Takai et al. (1998), as shown in Table 2, which is reconstituted by inhalable and respirable dust concentrations were measured in a substantial number of farms according to the animal species, animal ages, floor type of the livestock house, and aerosol size.

3. Materials and methods

3.1. Research site

The Anseong area in Korea was selected as the research site; this area suffered an FMD outbreak in 2002 (Fig. 1). The epidemiological investigation of FMD outbreaks in Korea analysed and selected appropriate research sites based on cooperation with the Animal and Plant Quarantine Agency (APQA), the cooperation of farm owners, sufficient weather data from meteorological observatories, and a suspected area of airborne FMD spread based on a prior epidemiological

Table 1 – Emission rate of the FMD virus and critical concentration for FMD infection according to animal species (Sørensen et al., 2000); TCID denotes tissue culture infectious dose.

	Cattle	Pig	Sheep
Emission Rate (log10 $TCID_{50}$ d^{-1})	5.06	7.16	4.94
Critical Concentration ($TCID_{50}$ m^{-3})	0.06	7.70	1.11

investigation (Wee et al., 2008). Table 3 shows farm information in the area of interest in Anseong during the 2002 FMD outbreak; the species and numbers of animals for each farm belonging to a single infected (or suspected) farm, and the animals were culled, including those on adjacent farms after confirmation of infection. The cause of the 2002 FMD outbreak was considered to be by travellers and foreign workers who had visited China, Mongolia, and East Asia, where FMD has frequently occurs (MAFRA, 2003). A major cause of the spread of the disease was thought to be by mechanical means by human and vehicle transmission. A value of 140 million USD was spent on farm support during the 2002 outbreak and additional costs were incurred from direct and indirect damage, such as culling livestock animals, environmental pollution, mental damage, and animal re-stocking.

The Anseong research area showed a clear spreading pattern during the 2002 FMD outbreak, which can be effectively used for model validation. Although most of the spread of FMD disease through the pig farms was by human, vehicle, animals, and other factors, farm 8 (rearing cattle) in Table 3 was without any direct contact with pig farms and this clearly showed the possibility of airborne spread since there was little human contact and no vehicle transmissions caused by feed and pharmaceutical company employees moving between pig and cattle farms.

Weather conditions in Anseong during 2002 outbreak were analysed to discover the relationship between FMD spread and hourly wind conditions (Fig. 2). On average a north-easterly wind was recorded from 1 AM to 9 AM with mild wind speed that was mostly <2 m s^{-1}. After sunrise, a westerly wind (which is the prevailing wind direction) caused airborne virus spread during the daytime. The peak period for livestock aerosol emissions from animal management, including feeding, cleaning, and other tasks, was recorded from 9 AM to 12 PM when high wind speeds >2 m s^{-1} was frequently recorded. The weather data showed an average air temperature of 20.3 °C and a relative humidity of 63% over two months. These are suitable weather condition for virus survival, which is recommended by values of under 27 °C for the air temperature and over 60% for the air relative humidity. The FMD spread pattern was predicted to be from a south-western to a north-eastern route following the direction of the prevailing wind.

3.2. *Weather data acquisition*

Climate data was linked to construct a database for the hourly air temperature, relative humidity, wind direction, wind speed, and precipitation at the research site. The Anseong area has five AWSs (automatic weather stations) operated by the KMA (Korea meteorological administration): Baegam (E 37.1618° N 127.3816° 126 m), Moga (E 37.1691°, N 127.4823°, 92 m), Iljuk (E 37.0906°, N 127.4770°, 84 m), Anseong (E 37.0087°, N 127.2672°, 36 m), and Bogae (E 37.0197°, 127.2919°, 82 m in elevation). An additional reference weather station was used to validate the airflow pattern that was simulated by CFD compared with weather data from AWSs. The weather station was installed in a flat open area where vehicle movement is rare, and there are no obstacles around (E 37.0807°, N 127.4469°, 105 m), as shown in Figs. 1 and 3. The height of wind measurements was 5 m from a hilly ground surface thereby avoiding the effects of surface roughness. Climate data from AWSs and the reference weather station was collected by STL-X16 data logger (STA Corporations, Ltd., Anyang, Korea), including the air temperature (°C), relative humidity (%), ground temperature (°C), wind direction (°), wind speed (m s^{-1}), leaf wetness (dimensionless), and precipitation (mm). The climate data were sent to a weather data acquisition server (WDAS) every 10 min by means of a wireless modem (Telit Wireless Solution, Co., Ltd., Seoul, Korea) using a code division multiple access (CDMA) technique. The WDAS was developed to store all of the measured data in a single observed weather database.

3.3. *Database for weather information*

The database management server saved real-time climate and weather data from the AWSs in Bogae, Moga, Iljuk, Anseong, and Baegam as well as from the reference weather stations installed in the research site for the validation of airflow patterns that are computed by the CFD simulation (Fig. 4). The climate and weather data were also used for the web-based forecasting system of livestock disease by changing its format to be suitable for the website (see Fig. 5).

KMA operates an automatic weather observation network and observed weather database that collects all of the hourly observatory data. In addition, KMA releases weather forecasts for the next 48 h at every three-hour interval, including the air temperature, relative humidity, and probability of

Table 2 – Dust concentration generated from pig farms (Takai et al., 1998).

	Inhalable dust concentration (size 3.7–7 μm)		Respirable dust concentration (size 0.091–1.1 μm)	
	Measuring farms	Average concentration (mg m^{-3})	Measuring farms	Average concentration (mg m^{-3})
England	76	1.87	75	0.24
Netherland	48	2.43	48	0.25
Denmark	64	2.76	64	0.26
Germany	68	1.95	68	0.18
Sum/mean	256	2.19	255	0.23

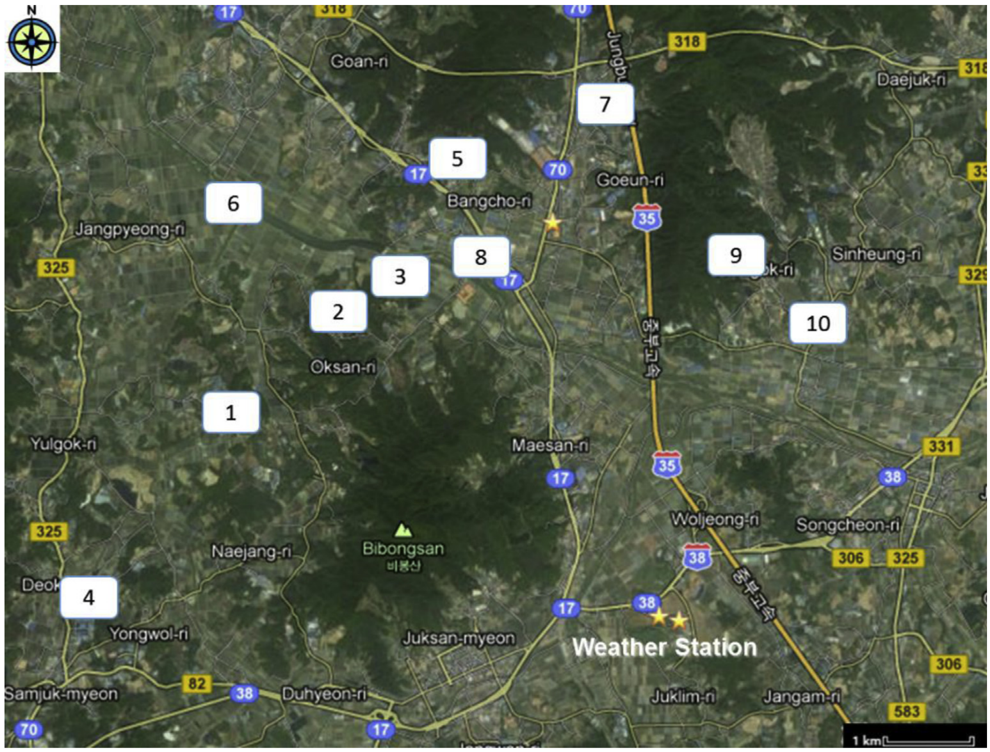

Fig. 1 – Satellite image and farm locations in the Anseong research site.

precipitation at 12-h intervals based on the outputs computed by numerical weather prediction models (Seo et al., 2007). The spatial resolution of the weather forecast had a mesh distance of 5 km. The forecast weather database was also collected in the observed weather database.

3.4. *CFD tool*

Open field operation and manipulation (OpenFOAM, version 2.1.1.) was used in this research. OpenFOAM is an open source CFD code that has no license cost for research as well as commercial purposes. It was developed by an object-oriented program system under LINUX OS and the C++ program language, while solving fluid dynamic problems by means of the finite volume method in Eq. (1). This program has advantages in terms of cost reduction, expandability of hardware scale, reduction in computation time, simplicity in adding functions, and production of a private programms that allows users to easily access the program package, although OpenFOAM is still a difficult program to operate since it has a text user interface, few manual options and little information.

An integrated total solution package was developed for airborne virus spread, including complex topography modelling, airflow analysis, virus spread analysis based on the weather forecasting in real time, and result derivation. However, this approach does make it possible for laymen to handle CFD following a manual written specifically for the application. The governing equations are the Navier–Stokes equations that solve the mass, momentum, and energy conservative equations for fluid mechanics. A standard k-ε turbulence model was used for dispersion modelling of

Table 3 – Farm information during the 2002 FMD outbreak in Korea; animals had been culled within a radius of 500 m; farm workers reported the FMD to a quarantine office on the Report Day, the FMD was finally confirmed by the authorities to be infected with the FMD on the Declaration Day. Infected animals and neighbouring animals were then culled.

Farm#	Report Day	Declaration Day	Breeding Scale (infected animals)	Number of animals culled
1	May 2	May 3	Pig 8300 (500)	10,817
2	May 10	May 11	Pig 1418 (8)	4872
3	May 10	May 11	Pig 11,028(8)	11,028
4	May 10	May 11	Pig 162(1), Cattle 116	3488
5	May 12	May 13	Pig 300 (18)	2471
6	May 18	May 19	Pig 1048(2)	1047
7	May 19	May 19	Pig 996(16)	8457
8	June 7	June 8	Cattle 78(1)	151
9	June 10	June 11	Pig 5429(13)	11,144
10	June 23	June 24	Pig 1869(6)	6322

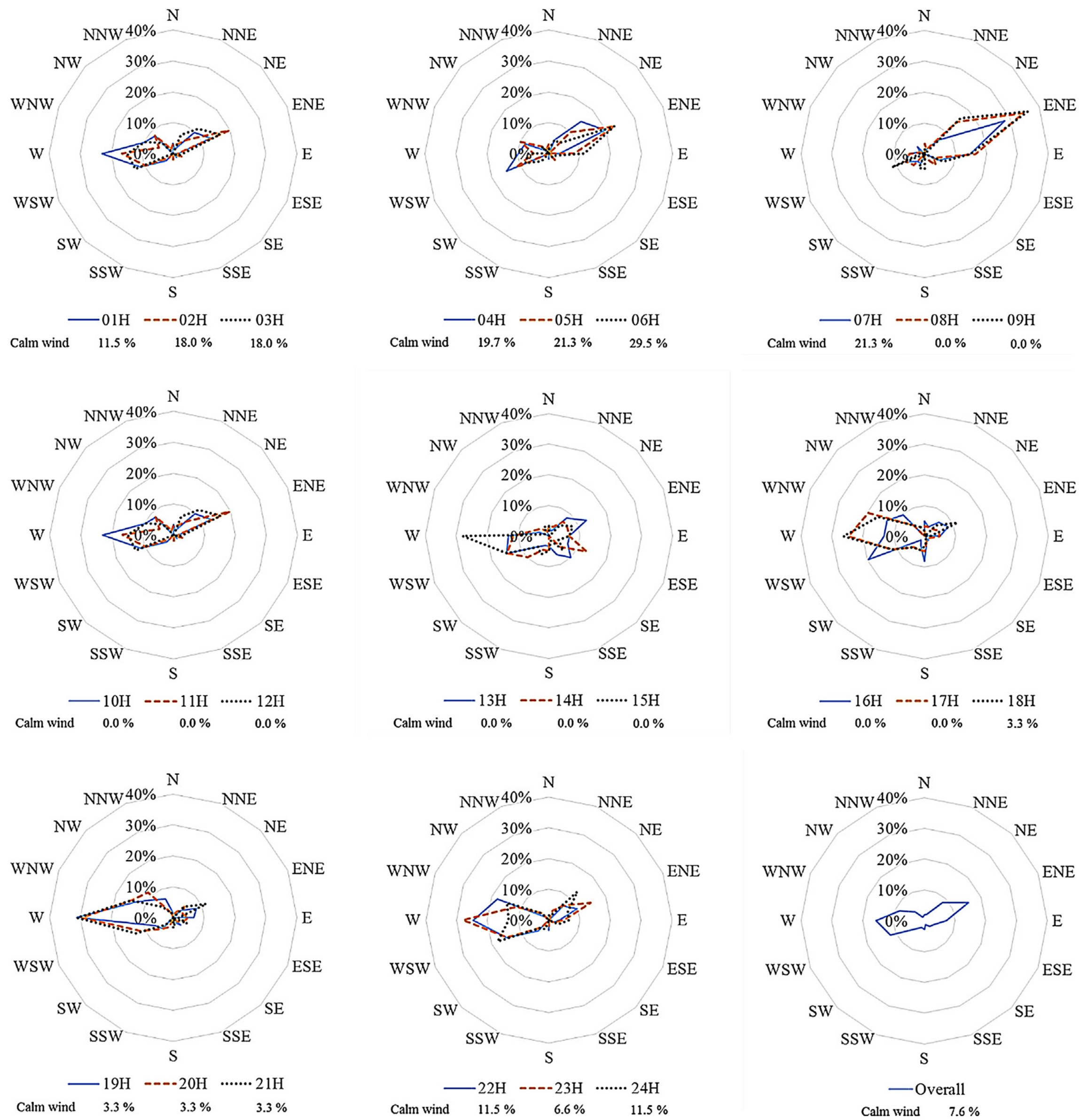

Fig. 2 – Hourly wind occurring during the 2002 FMD outbreak (May–June, 2002).

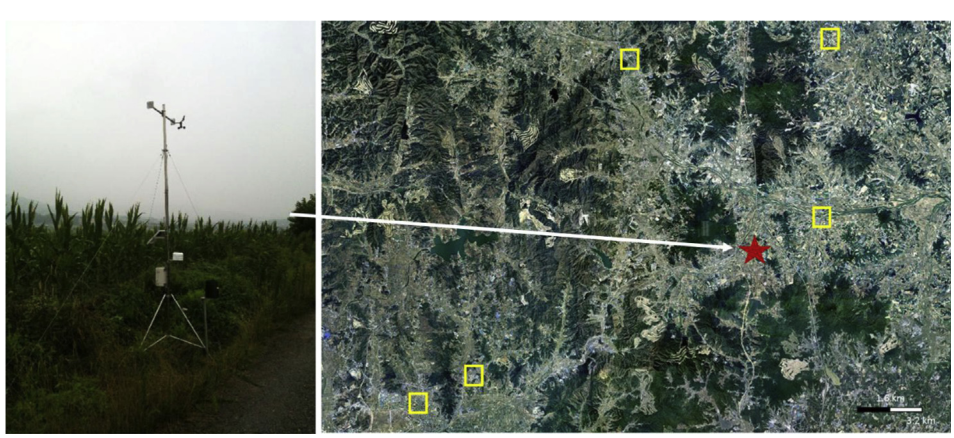

Fig. 3 – Reference weather station site installed at Seongwon Farm, Anseong, Korea.

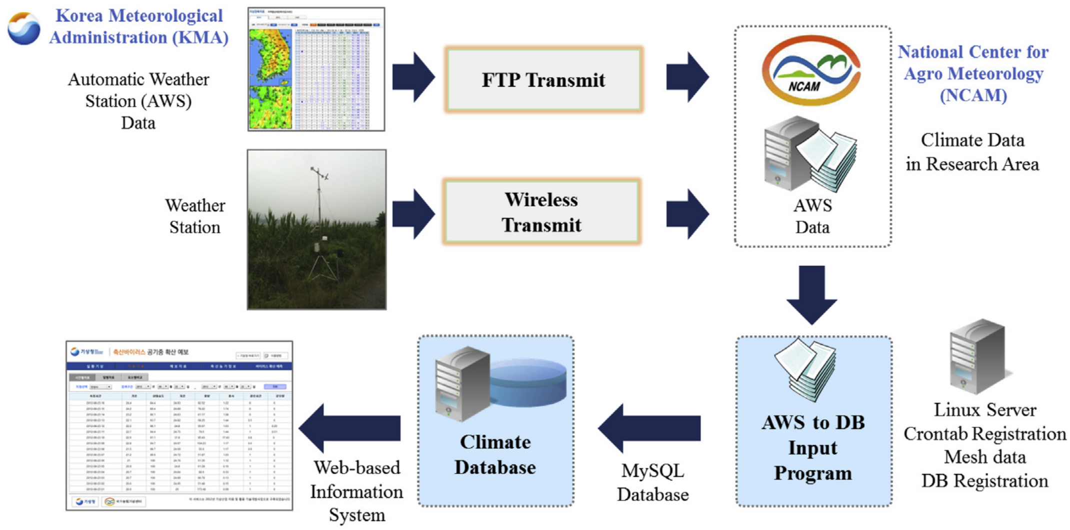

Fig. 4 – Flow chart for the construction of the climate and weather information database.

airborne contaminant (Li & Guo, 2008; Seo et al., 2010). Inlet conditions for boundary were calculated by reference data taken from AWS based on the vertical profiles for the inlet velocity (Eq. (2)), the turbulence kinetic energy (Eq. (3)), and the turbulence dissipation rate (Eq. (4)). After simulation of the airflow pattern according to the wind conditions, the virus spread simulation was followed by the scalar transport analysis that is given in Eq. (5).

$$\frac{\partial}{\partial t}(\rho U) + \nabla\cdot(\rho UU) - \nabla\cdot(\mu\nabla U) = -\nabla p \quad (1)$$

$$U(z) = \frac{u_*}{\kappa}\log\left(\frac{z}{z_0}\right) \quad (2)$$

$$k = \frac{u_*^2}{\sqrt{C_\mu}}\left(1 - \frac{z}{\delta}\right) \quad (3)$$

$$\varepsilon = \frac{u_*^3}{\kappa z}\left(1 - \frac{z}{\delta}\right) \quad (4)$$

$$\frac{\partial}{\partial t}\left(\rho\phi\right) + \nabla\cdot(\rho u\phi - \nabla\Gamma\phi) = S_\phi \quad (5)$$

where, t is time (s), ρ is density (kg m^{-3}), U is velocity (m s^{-1}), p is constant pressure (Pa), u^* is the fiction velocity (m s^{-1}), κ is the von Karman constant, z_0 is the height of the surface roughness, $C\mu$ is the empirical constant of the turbulence model (approximately 0.09), δ is the bound layer depth (m), ε is the turbulent dissipation rate (m^2 s^{-3}), Γ is the diffusion coefficient, and S_ϕ is the source term.

3.5. *Research procedure*

Figure 4 shows a flowchart to make a WebFoS, which can provide farm information that relates to livestock disease and airborne virus spread, interworking CFD simulation and real time weather forecasting system that is used to predict an expected livestock disease spreading route. The research procedure was divided into five steps.

(1) A virus emission calculation algorithm was derived by considering the animal species, characteristics of livestock houses, numbers of animals, and other factors. The calculated emission rates were used as initial conditions for the point sources of FMD-infected farms. The

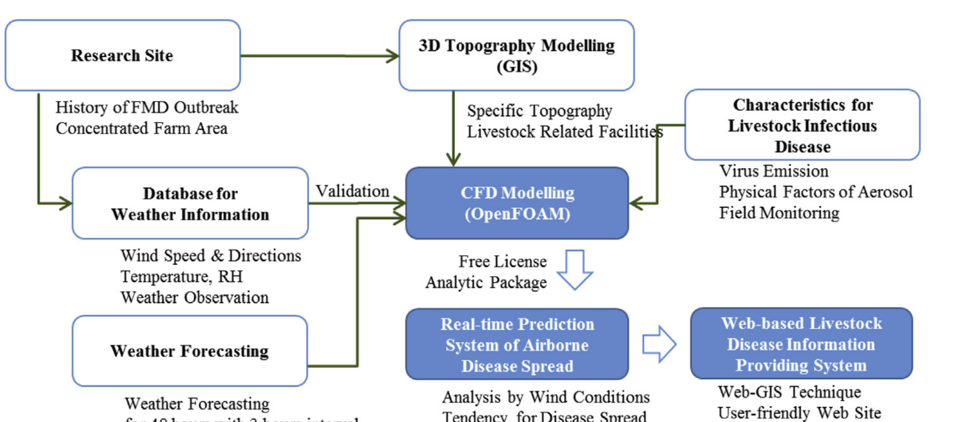

Fig. 5 – Flowchart for development of web-based information system.

Table 4 – Respirable aerosol concentrations by animal species, ages, and floor types based on the measurement by Takai et al. (1998) (Unit: mg m^{-3}).

Cattle		Pig	
Dairy, litter	0.372	Sows, litter	0.638
Dairy, slat	0.400	Sows, slat	0.934
Beef, litter	0.550	Fatteners, litter	–
Beef, slat	0.538	Fatteners, slat	2.019
Calves, litter	0.308	Weaners, litter	0.710
Calves, slat	0.350	Weaners, slat	1.193

concentration of the virus was considered to produce a standard for forecasting that could help make time for the preparation of countermeasures and strategies to combat the FMD outbreak.

(2) The WDAS using AWS data from KMA and the weather station were constructed to provide real-time weather forecasting for prediction of disease spread and past weather information for validating CFD-computed airflow patterns.

(3) A CFD simulation model was designed to predict airborne spread of virus. A three-dimensional complex topography was modelled for the Anseong research site based on GIS information. It was necessary to calculate the CFD simulation model as rapidly as possible to enable real-time forecasting of airborne virus spread based on 48-h weather forecasts updated at three-hour intervals and provided by KMA. If all information was simulated at the same time, including the airborne spread and airflow pattern, prompt forecasting would be impossible due to calculation time involved. Therefore, a two-step simulation was conducted to dramatically save on computation time and to maintain result accuracy; first, airflow patterns for eight wind directions and fifteen wind speeds from 0.2 to 3.0 m s^{-1} at 0.2 m s^{-1} intervals were simulated and saved as basic airflow data; then, the scalar transport for airborne virus was modelled from infected livestock farms for next 48 h using the saved basic airflow data.

(4) An integrated server system was then constructed to inter-work real-time information that was obtained through steps (1)–(3). Then, CFD simulation was conducted at three-hour intervals to predict airborne virus spread based on the interworking between the specific topography, farm information, and real-time climate forecasting. The time dependent scalar transport of the airborne virus was calculated using preceding data file for calculating airflow patterns according to wind speeds and wind directions.

(5) A WebFoS was developed to provide airborne spread of livestock disease pattern, weather conditions, and farm information, focusing on user demands, including farm managers and policy decision-makers acting against preventive measures. The WebFoS was able to support and obtain the past, present, and future weather data and to utilise the basic data for epidemiological investigation, including airborne virus spread, policy decisions, and farm management.

4. System development

4.1. FMD emission rate

To simulate airborne spread of disease from infected livestock farms, a logical algorithm for calculation of FMD virus emission rate is required based on scientific experiments. The virus emission rate from an infected single animal were suggested by means of controlled laboratory experiments using real animal and tissue culture experiments in terms of the $TCID_{50}$ unit (Sørensen et al., 2000). However, these data could not be used for practical purposes to calculate the overall virus emission rate with regard to livestock aerosols in infected livestock houses because emissions alter according to the various characteristics of the livestock houses.

The aerosol concentrations were measured according to the animal species, age, and floor type, as shown in Table 4 (Takai et al., 1998), which can be used as practical data to calculate the livestock aerosol emission rate in terms of farm scale. The calculation algorithm for the FMD virus emission rate was suggested by a combination between virus-based scientific information and field-measured aerosol concentration according to animal and livestock characteristics, as shown in Fig. 6. The emission rate of livestock aerosols was calculated by the algorithm while considering the animal, livestock house, and farm operation characteristics in Eq. (6); then, the value was used as input data for the generation rate at the point sources for each infected livestock house. The equation used included information as follows: the livestock aerosol concentration according to the animal species, ages, and floor types in accordance with the database table, number of animals in the infected livestock farm, recommendation of livestock density, time interval for CFD simulation (typically set at 1 s), and an assumption of an infection ratio of 10%, which can be changed by the user for each outbreak situation when making decisions concerning preventive measures.

$$C_{aerosol} \times P_{infection} \times N_{animal} \times A_{animal} \times s^{-1} = Q_{point} \quad (6)$$

where $C_{aerosol}$ is the livestock aerosol concentration by animal species, ages, and floor type (mg m^{-3}), $P_{infection}$ is the infection ratio in an infected livestock house (%), N_{animal} is the number of animals in a livestock house (head), A_{animal} is the recommended rearing area (m^3 $head^{-1}$), s is the time interval for CFD simulation (s), and Q_{point} is the livestock aerosol emission rate for attaching a virus (mg s^{-1}).

There are few studies on decisions about preventive lines in terms of airborne virus spread. A logical inference is possible from the FMD virus emission rate and the critical concentration for FMD infection (Sørensen et al., 2000). A first infection line was determined by a value of 0.0929 mg m^{-3} based on the relationship between CFD computed livestock aerosol concentration and the critical virus concentration of FMD infection for pigs as shown in Tables 1 and 2, while a second infection line was determined to have a value of 0.0248 mg m^{-3} with the same procedure when considering cattle. These values corresponded to 0.051% and 0.014% from livestock aerosol concentrations at certain point sources that were emitted from the infected farm having 1000 pigs with the

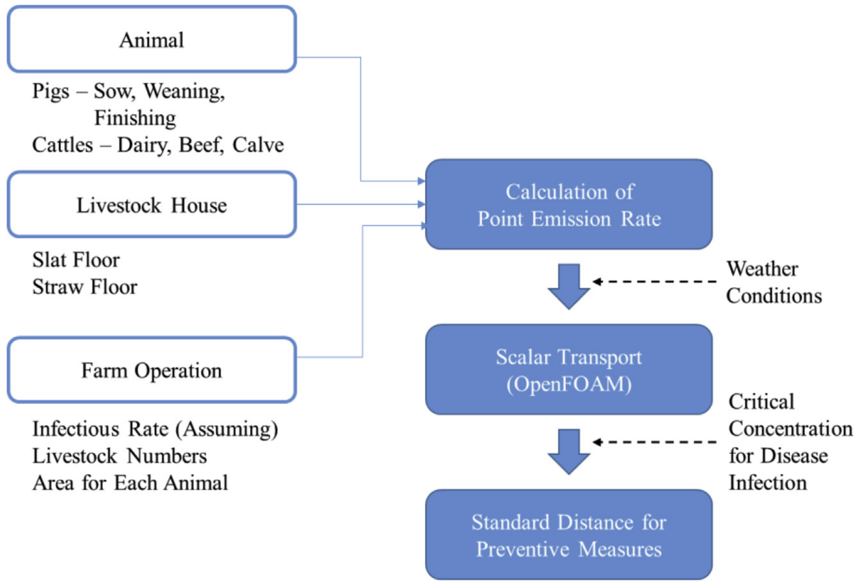

Fig. 6 – Algorithm for the calculation of the FMD virus emission rate in terms of the livestock virus for the point sources in the CFD simulation model.

infection ratio of 10%. These lines can be used for reference concentrations on the forecasting of airborne FMD spread, providing to farm managers and decision makers preventive measures against FMD outbreaks.

4.2. *3D topography modelling (GIS)*

A complex topography was designed from a numerical map of the area that was scaled by 1:25,000 and provided by the National Spatial Information Clearinghouse supported by the Ministry of Land, Infrastructure and Transport in Korea, using ArcGIS (version 9.2, Esri Inc., Redlands, California, USA); the specific steps were as followed: 1) extracting a contour map, 2) creating a triangular irregular network (TIN), and 3) converting to a digital elevation model (DEM) as shown in Fig. 7. Using the DEM information, a three-dimensional surface for the computational domain was designed with an octagon that has a radius of 11 km, with the research site as its centre (Fig. 8). Only one computational domain was considered so as to reduce the error between the other wind directions. A buffer area, 56.6 by 56.6 km in size, extended the boundary of the computational domain to stabilise the inflow and outflow airflow pattern at each boundary and to obtain solution convergence. Without this buffer area, the airflow that started from the mountainous boundary would demonstrate unpractical airflow patterns and wind speeds. Therefore, the buffer area was added by stretching the mountainous area until the height of ground surface had a value of 0 m.

To simulate the airborne spread of livestock aerosols, point sources were assumed at the coordinates of each coordinate for the livestock farms in the research site. This approach was taken because farm size is very small compared to the overall computational domain sized by 40 km × 32 km × 1.7 km height, and a livestock aerosol emitted from a ventilation system that included roof and windows was quickly dispersed in the air and was dispersed through an airflow pattern

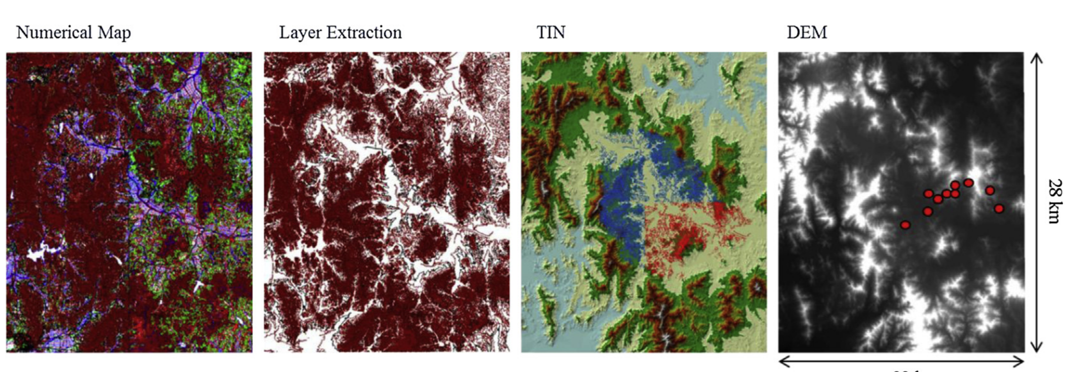

Fig. 7 – Process for a three-dimensional ground surface for the computational domain from a numerical map to a digital elevation model (DEM) in the research site: the red circles in the DEM map represent the farm locations.

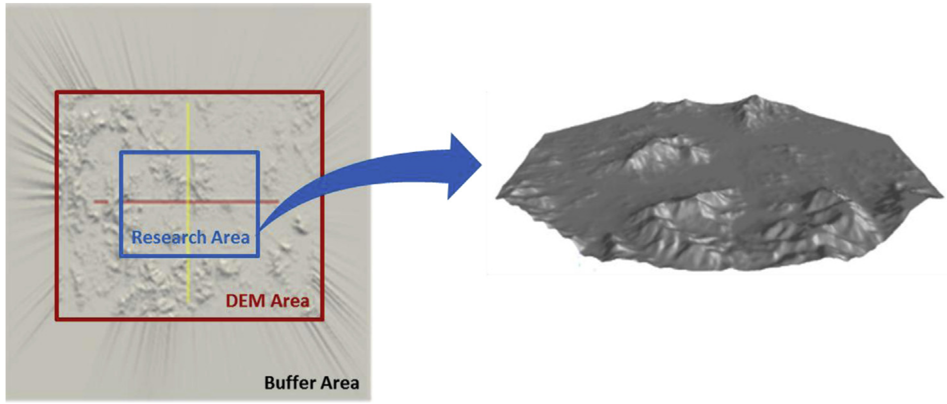

Fig. 8 – Three-dimensional ground surface considering the buffer area for enhancing the model convergence stability.

formed by wind and topography while considering the modelling scale. The aerosol concentrations from point sources were calculated by considering the livestock species, farm scale, floor types, and other factors as overall emission rates.

4.3. *Real-time CFD simulation interworked with weather forecasting*

A short computation time is a decided advantage for a web-based forecasting system. An automated system for the overall process also makes it easy to manage the forecasting system more systematically, especially in a real-time updating system compared to a passive control system. Ground surface modelling using complex topography and a database for airflow patterns according to various wind directions and speeds was used to make a basic airflow database. Using the basic airflow database, a real-time scalar transport simulation for the airborne spread of FMD disease was conducted every three-hour to forecast the subsequent 48 h using three routine processes by interworked with weather forecasting, as shown in Fig. 9: 1) database construction for weather forecasting and measurement from AWSs and weather stations, 2) CFD simulation of virus scalar transport using the weather forecasting and time-dependent airflow pattern using precedence basic airflow database, and 3) forecasting a system update on the web-based forecasting system for airborne spread of livestock disease.

Firstly, the weather data from AWSs and weather forecasting from KMA were automatically collected in the server using the MySQL (version 5.095, http://www.mysql.com) database management system and an Apache web server (version 2.2.3., http://httpd.apache.org) operated by Linux OS (CentOS release 5.6). Secondly, the CFD modelling using OpenFOAM was carried out to predict airborne FMD virus spread based on the weather forecasting, as shown in Fig. 10. The data for airborne virus spread was then converted into GIS information form and was updated to the web-based server system to create an airborne virus spread prediction map as a final result. Thirdly, the WebFoS application for the airborne spread of livestock disease was constructed to distribute the FMD-related information, including the prediction map of airborne FMD spread, weather observatory data, weather forecasting, and farm information. The webpage (http://livestock.ncam.kr) in Korean and English was built using HTML, CSS, and OpenLayers (version 2.13, http://www.openlayers.org) for the expression of GIS information and Java (standard edition 7, http://www.java.com) for data collection and processing. This server has been operated on 2.33 GHz CPU (Intel Xeon quad-core) with 28 GB RAM, 6TB HDD, and a 100 Mbps internet system. The overall process can be maintained

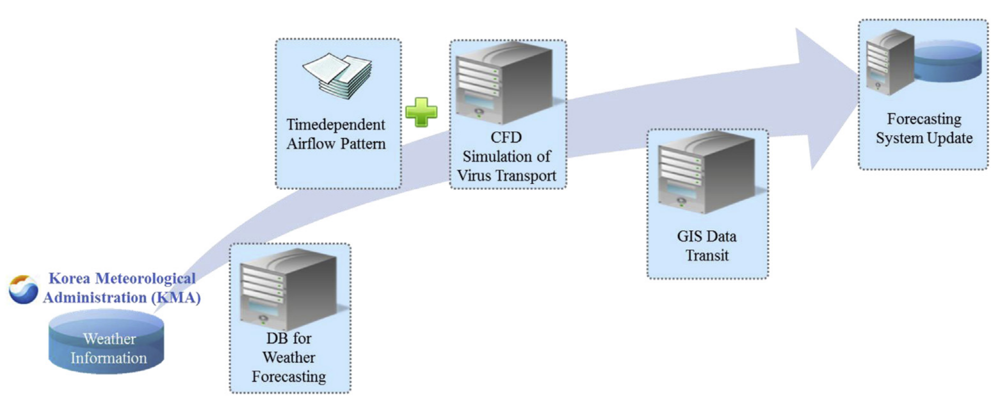

Fig. 9 – Overall system structure of the web-based warning system for airborne spread.

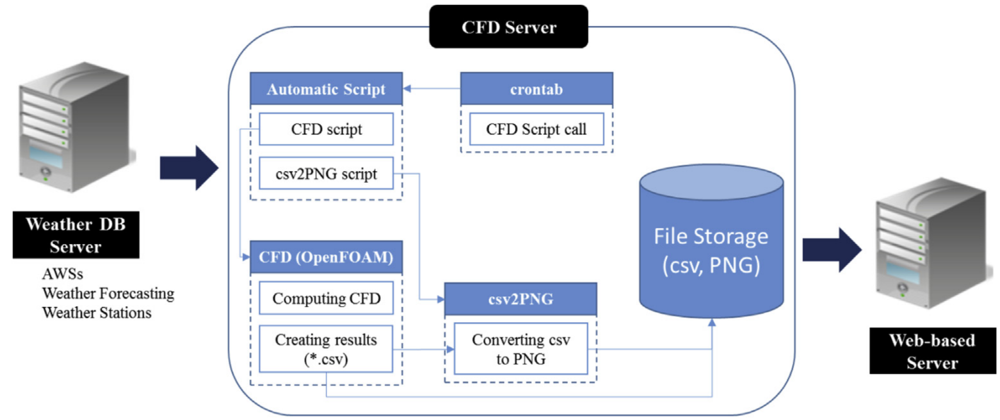

Fig. 10 – Detailed process of CFD simulation using OpenFOAM for calculating virus scalar transport from weather forecasting

without technical knowledge of the internal system providing a "black box" to the system administrator.

5. Results and DISCUSSION

5.1. *Validation of CFD computed airflow*

The CFD computed airflow was validated with observed data that was measured by AWSs and the installed reference weather station when the weather conditions were relatively stable during over 8 h period, considering the size of computational domain after analysing the weather database during the overall period. The CFD model carried out computations based on steady-state conditions during each case for the wind directions and wind speeds, which is not common in real situations. Continuously changing the wind speed would establish an unsettled airflow pattern from the inlet boundary to the outlet boundary and make convergence difficult. Therefore, meteorological measurements for different locations at the same time could not be

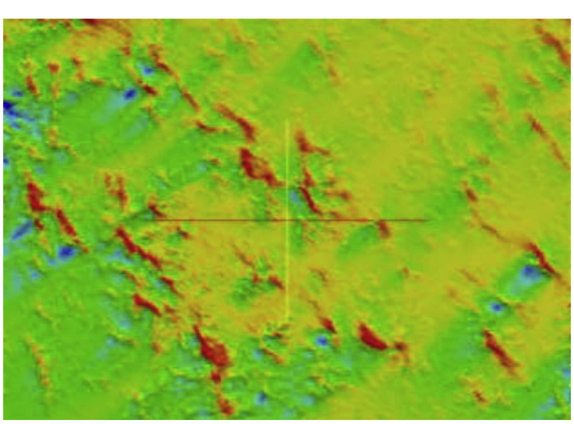

Fig. 11 – Colour distribution map for the wind speeds at 10 m above the ground surface in the complex topography; the colour represents 0 m s^{-1} in blue and over 1 m s^{-1} in red.

used to validate the CFD simulation model at steady-state conditions.

Figure 11 shows an example of the wind speed distribution map from the CFD computed airflow pattern at a 1.0 m s^{-1} wind speed and with a north-easterly wind direction; a red colour represents an increase in the wind speed to over 1.0 m s^{-1} passing through a hilly and mountainous area and a blue colour represents a decrease in the wind speed to under 1.0 m s^{-1}. For two selected periods, while maintaining similar wind conditions for more than 6 h, wind measurement data at two of the AWSs (Iljuk and Baegam) and weather stations were compared to the CFD computed airflow pattern for its validation. The CFD computed wind directions at each observation location were shown an error of 1.2% compared with measured wind directions, as shown in Table 5. The difference in the average wind speed between the CFD computed values and AWS measured values showed an error of 11.6%, which is reasonable for CFD validation, particularly when considering the size of the computational domain.

A very large computational resource would be required to simulate airflow pattern and airborne virus spread simultaneously. For a real-time forecasting system, a calculation algorithm was developed to dramatically save on computational time while focusing on the scalar transport of an airborne virus using updating weather forecast and an already computed airflow pattern according to various wind directions and speeds. The CFD computed spread pattern for airborne livestock aerosol spread showed complex behaviour when there was aerosol generation from an infected farm, dispersion by complex topography, and changing by airflow patterns, as shown in Fig. 12. In this case, a high concentration of livestock aerosol was predicted to stagnate beyond the mountains (in red) (in web version) due to an eddy, and its airborne spread was well simulated by means of changing the wind directions and speeds.

5.2. *Web-based forecasting system (WebFoS)*

The WebFoS application was developed to provide information related to livestock disease from weather forecasting and past and present weather observatory data monitored by

Table 5 – Comparisons of wind speeds and directions between the CFD computed and AWS measured airflow pattern for CFD validation; WS: wind speed ($m\ s^{-1}$), WD: wind direction (°).

	Case 1 (1 PM, Sep. 16, 2012)				Case 2 (1 PM, Sep. 26, 2012)			
	Measured		CFD computed		Measured		CFD computed	
	WS	WD	WS	WD	WS	WD	WS	WD
Weather Station	2.0	44.0	2.1	44.1	1.3	91.1	1.3	91.3
Iljuk	1.3	35.7	1.9	45.6	0.8	94.9	1.3	92.2
Baegam	1.5	42.4	1.3	37.5	1.3	101.9	0.9	95.4

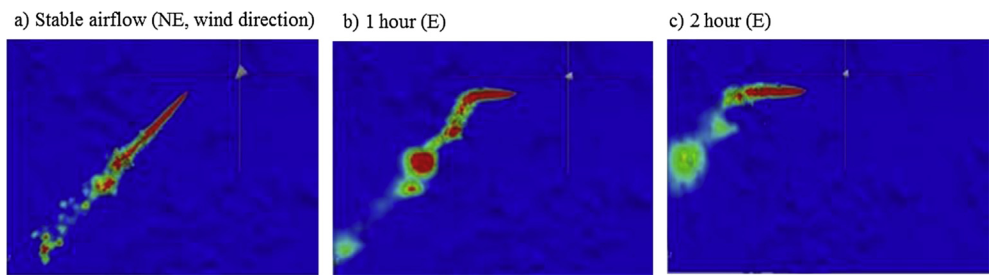

Fig. 12 – Sample of the scalar transport of livestock aerosols as computed by CFD; a) during stable airflow with north-east wind direction, b) 1 h, and c) 2 h after wind direction was changed from north east to east.

Table 6 – Geographic locations and observed elements of automatic weather stations.

AWS	Location	Observed element	Longitude (°)	Latitude (°)	Elevation (m)	Temporal resolution (min)
Reference site	Iljuk	Air temp., ground temp., RH, rain, leaf wetness, wind direction, wind speed	127.4469E	37.0807N	105	1
Automatic Weather Observation Network by KMA	Bogae	Air temp., RH, rain, wind direction, wind speed	127.2919E	37.0197N	82	60
	Moga		127.4823E	37.1691N	92	
	Iljuk		127.4770E	37.0906N	84	
	Anseong		127.2672E	37.0087N	36	
	Baegam		127.3816E	37.1618N	126	

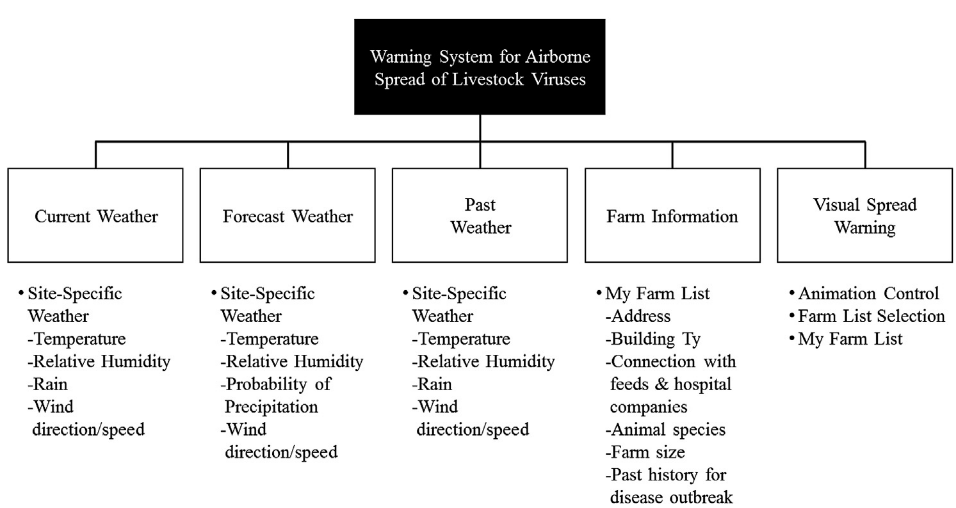

Fig. 13 – Information tree provided by WebFoS.

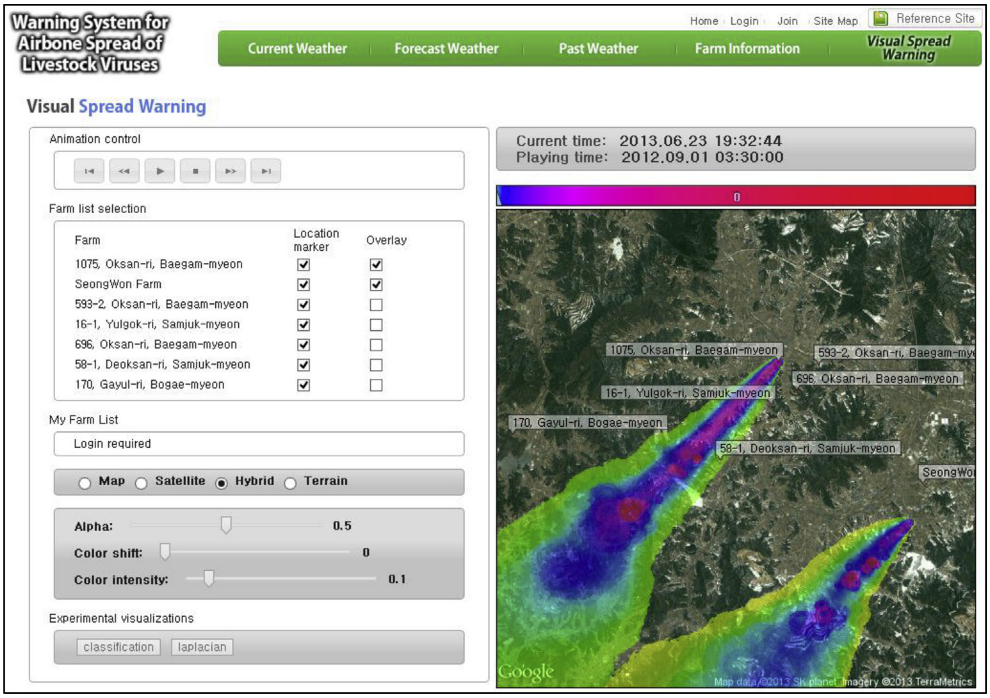

Fig. 14 – A sample image showing a visual spread warning of the web-based forecasting system for airborne spread of livestock viruses.

AWSs and weather stations, as shown in Table 6. Weather data during certain periods required by users can be retrieved in table form. The prediction of airborne virus spread was provided in an animation form with time-dependence over the GIS map, including the administrative district map, road map, terrain map, and satellite image, with super resolution of 5 m as a background layer by means of the web technology and GIS. The WebFoS application has five main categories, current weather, forecast weather, past weather, farm information, and visual spread warning, as shown in detail in Fig. 13

The WebFoS was provided to users via a web–map interface, as shown in Fig. 14. The forecast animation was created for the next 48 h with thirty-minute intervals based on the

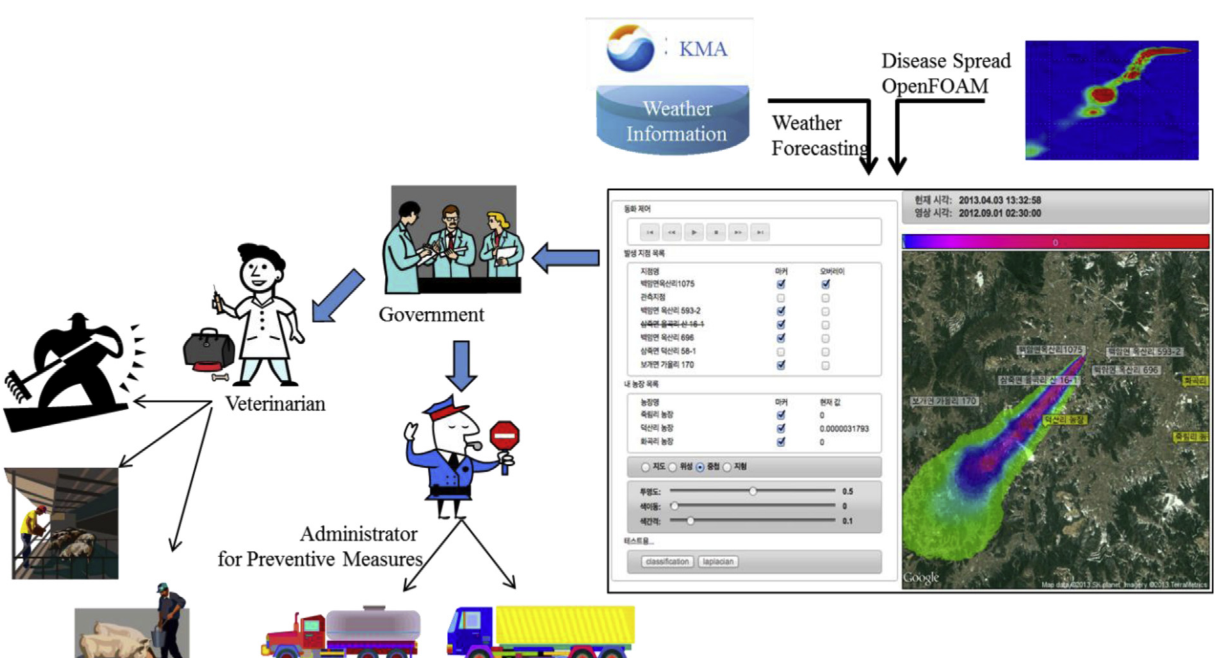

Fig. 15 – Application plan of the WebFoS.

weather forecast from KMA. The concentration of livestock disease virus and its spreading route through airflow patterns from infected farms can be expressed in a time-dependent way. Various seasonal and periodic data have been provided in the WDIPS, including farm information, area, spread distance, and the effects of neighbouring farms. Interpolated data for predicted virus concentrations were provided on the map by a hovering cursor. When a user joins as a member with farm information, the predicted value of the airborne virus concentration can be shown by time series of graphs from neighbouring point sources of infected farms.

The WebFoS provides various visual expression modes using a line chart, scatter point, and stacked area bar to maximise the dissemination of airborne livestock spread information and relative farm information, including the address, building characteristics, animal species, animal age, number of animals, feed and, pharmaceutical company, past history of disease outbreaks, wastewater treatment, and ventilation system. The information will be provided to local governments and quarantine headquarters to assist the making of emergency preventive measures and decision making, as shown in Fig. 15.

6. Conclusions

A WebFoS for livestock disease was developed for investigating epidemiological interrelationships between livestock infectious diseases and weather conditions and to set up a prediction technique based on computational fluid dynamics (CFD). The WebFoS can predict airborne virus spread for the next 48 h based on the real-time weather forecasting supported by the KMA. Stored data can be used for user-friendly web-based services to make preventive measures and farm management strategies against livestock infectious diseases. The WebFoS could be utilised for other livestock infectious diseases by means of a minor adjustment of the input environment and flexible criteria that are suitable to other animal species. In the future, the weather information service should be expanded to the biometeorology industry, and information concerning airborne virus spread can be used to reduce damage from livestock infectious diseases by predicting the routes used for virus spread.

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