1. INTRODUCTION

Uncontrolled fires have devastated both human life and property throughout history. While water has always been seen as a possible suppression method, recently interest in the use of water for fire suppression has been renewed by the signing of the Montreal Protocol in 1987, prohibiting the use of the popular suppressants Halon 1301 (CF$_2$Br) and 1202 (CF$_2$Br$_2$) because they were found to deplete the ozone layer. The use of water sprays continues to be a leading candidate for Halon replacement because it is environmentally friendly, non toxic, and inexpensive.

Because of water’s high efficiency in extracting energy during its phase transformation from liquid to vapor, high local gas fire temperatures can be substantially reduced. This temperature reduction reduces fuel devolatilization or evaporation and suppression occurs. In addition, the vaporized water occupies the local space, displacing the local oxygen concentration and preventing reignition [1].

This objective of this study is to consider the use of high-speed water spray which substantially reduces the heat flux radiated to the fuel surface by distorting the fire geometry [2]; the shape of the combustion zone can be distorted using a water spray momentum greater than the momentum of the fire buoyancy force. It is crucial to provide the droplet size capable of delivering sufficient momentum to overcome the fire buoyancy force. For this reason, we have conducted a series of simulations in which we vary the mean droplet size of the water spray system, as well as the spray injection speed. Here we define that the optimum fire suppression condition is found when the selected local flame temperature is reduced to a room temperature of 300 K at the fastest rate with respect to others cases under the fixed amount of water supply (i.e., fixed water mass flow rate).

The scope of this study is limited to understanding the key physics parameters in gas-phase fire suppression from sprinkler (or water mist systems) which are commonly deployed in a ceiling mounted configuration. This study uses commonly-used engineering subgrid scale (SGS) models, rather than the advancement of new SGS models.

The models will be discussed following a selected literature review in the next section. The model performance against a selected data set will then be demonstrated. A parametric study showing the effects of spray jet momentum and droplet size will be given. Lastly, conclusions are drawn on initial spray momentum, droplet sizes, and nozzle configuration that result in preferred fire suppression.

2. MODELING DESCRIPTION

2.1 Governing Equations

Numerical simulations are conducted using Sandia’s fire field modeling code, VULCAN. The Eulerian gas phase system is based on an unsteady Reynolds-averaged Navier Stokes (RANS) formulation employing a standard $k$-$\varepsilon$ isotropic turbulence closure model [3]. The “Eddy Dissipation Concept” (EDC) combustion model of Ertevag and Magnussen [4] is used to model turbulent combustion as extended by Tieszen and Black [5] and Hewson et al [6] to include the effects of flame suppression. Details of the flame suppression will be given in the next section. Soot combustion and absorption properties are based on the work of Tesner [7] and a discrete transfer method is used to solve for the radiation heat transfer.

The gas-phase flow is calculated on a Eulerian staggered Cartesian grid using the pressure correction method of the SIMPLE algorithm [8]. The second order upwinding and centered scheme are used for the convective and diffusion terms, respectively, in solving the transport differential equations.
The water spray model is based on a Lagrangian stochastic separated flow approach [9,10]. Evolution equations for collections of droplets with similar sizes and initial conditions, denoted as parcels, are used to reduce computational cost. The parcels are advanced under the influence of modeled turbulent fluctuations in the gas-phase properties. Maxey and Riley’s [11] momentum equation for a small rigid sphere in a non-uniform flow is used, as well as the drag model of Chhabra et al [12] and the correlation by Ganser [13]. Evaporation is modeled using a thin skin model with standard convective correlations for heat and mass transfer. Droplet-droplet collisions are modeled using the model of Ko et al [14]. This approach only accounts for either droplet-droplet ‘bouncing’ or ‘coalescence’, and not a droplet-droplet ‘shattering’ effect that produces additional drops. The ‘shattering’ effect may become important for the head-to-head colliding sprays [15]. Since all droplets are moving in the same direction in our spray, the “shattering” is highly unlikely to occur. Droplet breakup due to aerodynamic forces is modeled using the Taylor Analogy Breakup (TAB) Model of O’Rourke and Amsden [16].

Turbulence models are introduced at the parcel and sub-parcel level to account for the effect of local fluctuations in the velocity field while the rest of the thermo-physical variables are approximated by their corresponding time averaged values. The velocity-fluctuation models serve to increase the droplet dispersion, mimicking the effects of unresolved turbulent eddies. These unresolved turbulent motions are significant for the present high-pressure spray that generates substantial turbulent kinetic energy. These unresolved turbulent motions are decomposed into parcel and sub-parcel models. The parcel turbulence model accounts for the effects of turbulent eddies perturbing the parcel trajectory and is based on the random walk model of Gosman and Ioannides [17], as modified by Shuen et al [18]. Within a parcel, the spatial distribution of particles is assumed to be of Gaussian form. The standard deviation of this spatial distribution evolves with time for each parcel as discussed by Zhou and Yao [19].

2.2 Fire Suppression Model
Within VULCAN [20], chemical reactions are greatly simplified, reflecting the predominance of mixing processes in fires. This simplified treatment of kinetics is not sufficient for suppression predictions, and suppression criteria are determined by employing a subgrid scale suppression model. The VULCAN suppression model is based on the concept of a critical Damkohler number for extinction where the Damkohler number represents the ratio between the chemical and fluid mixing time scales. This captures the physics of both oxygen depletion and cooling of the flame in fire suppression because both act to increase the chemical time scales. The chemical time scales are determined by conducting a series of computations of the blow-out limits for a perfectly-stirred reactor (PSR). The PSR approximation is consistent with the subgrid EDC combustion model which treats the mixture distribution as discrete delta functions for the flame zone and surroundings, effectively a Le = Sc = 0 approximation within the flame zone. The PSR results are pre-calculated using the CHEMKIN II [21] software package PSR module [22]. This chemical time scale, the PSR blow-out time scale, is parameterized as a function of the suppressant-reactant mixture composition and temperature. The fluid time scale is taken to be the Kolmogorov time scale based on standard turbulence theory, \( \tau_D = 0.41(\nu/\epsilon)^{1/2} \), where \( \nu \) and \( \epsilon \) are the molecular viscosity and the turbulent kinetic energy dissipation. The Damkohler number is then the ratio of this fluid time scale to the chemical time scale, determined from the PSR calculations, and for Damkohler numbers below a critical value the flame is locally extinguished, and the source terms in the code are set to zero. The critical Damkohler number for extinction was determined from jet blow-off studies [23] to be 1.367, and is thus independent of the suppressant. A similar criterion for flame extinguishment has been recently used by Koutmos [24] for LES, but the Damkohler number comes from a dynamic length scale ratio rather than being constant.

For mixtures of suppressants, mixing rules are used that allow the mixture mole fraction of suppressant to be determined using the following expression:

\[
\frac{1}{X_{\text{lim}} - X_{\text{mix}}} = \sum_{\text{species}} X_{\text{species}} \left( \frac{X_{\text{species}} - X_{\text{mix}}}{X_{\text{species}} - X_{\text{lim}}} \right)
\]

where \( X_{\text{lim}} \) is the suppressant mole fraction that extinguishes the flame for a specific suppressant species, \( X_{\text{species}} \) is the mole fraction of that particular suppressant species divided by the total suppressant mole fraction, and \( X_{\text{mix}} \) is the suppressant mole fraction for extinction for the suppressant mixture. These mixing rules work for suppressants that are mostly thermal in nature and so are well suited for studying the effects of water on flame suppression, but also allow the joint consideration of agents like CO\(_2\) or even halofluorocarbons.

3. MODEL EVALUATION
It is necessary to show the performance level of the current model by comparing the numerical prediction of the model against experimental data. In this section, the fire scenario of Chow et al [50] is chosen for our comparison study. In that experiment, a local gas temperature history was recorded using a thermocouple (TC1-7) located at 0.5 m directly above the gasoline pool fire (0.5 m diameter) as shown in Fig. 1. To fully ignite the 0.5 m diameter fire took about 8 sec. The water spray was injected at \( t = 60 \) sec, the time at which the fire was at quasi-steady state. Data was recorded up to \( t = 400 \) sec. The mean droplet size of the commercial water spray was about 340 \( \mu \)m. The total mass flow rate was \( m = 0.2 \) kg/s.

In the simulations, the droplet injection speed was varied (within the range \( 10 \text{ m/s} < U_{m} < 20 \text{ m/s} \) ) since this information was not reported by Chow et al [48], while the mean droplet size and mass flow rate were taken from their paper. The time step used for the gas phase simulation was \( \Delta t_{\text{gas}} = 0.1 \) s while the sub-cycling time step for the liquid phase was around \( \Delta t_{\text{spray}} \approx \Delta t_{\text{gas}}/100 \) s, set by the stability criterion implemented in the fire suppression code with the given maximum injection speed of the water spray. The computational mesh was 110,400 nodes (60 x 46 x 40) with refined grid resolution around the pool fire to better capture the detailed interaction between the water droplets...
and the flame surface region. The cone angle of the spray was set as \( \vartheta = 60^\circ \) and the spray injection was initiated at \( t=60 \) sec, consistent with the experimental operating conditions of Chow et al. [25]. Statistics on the spray characteristics were collected at intervals of 1 sec, starting from \( t = 80 \) sec to 400 sec (thus 320 samples). The total number of computational parcels injected was 1.28 million parcels during 320 sec spray injection duration (or 40000 parcels/sec), which allows sufficient statistical resolution. The initial droplet size distribution was assumed to be the Rosin-Rammler distribution shape (i.e., \( PDF(D) = \left[ D^{-1.1} / X \right] \exp \left(-D/ \left(D/ \langle D \rangle \right)^{1.1} \right) \)), where \( D \) is the droplet diameter and \( X \) is the characteristic droplet size) with the corresponding dispersion coefficient of \( q = 3 \), deduced from the measurement obtained for a typical commercial water sprinkler according to Widmann [26].

The local gas temperature measurement was taken at the location denoted TC1-7 (see Fig. 1). The temperature history there is shown in Fig. 2 and is compared with the computational predictions. As shown in Fig. 2, it took about 60 sec to reach maximum value, \( T_{\text{gas}} = 913 \) K. It is possible that the maximum temperature could have been higher than 913 K if the water spray injection had occurred later than at 60 sec. Predicted higher values of temperature may be due to heat losses to the wall surfaces that are not accounted for in the current study where the walls are assume to be adiabatic.

Four droplet injection speeds, \( U_{\text{inj}} = 10, 12.5, 15, \) and \( 17.5 \) m/s, are considered to study their effect on suppression. While suppression was not achieved at \( U_{\text{inj}} \leq 12.5 \) m/s, it was predicted for injection velocities \( U_{\text{inj}} > 15 \) m/s. This indicates that there is a critical droplet injection speed which yields suppression.

In Figure 3, the time-averaged gas temperature contours and the droplet trajectories for \( U_{\text{inj}} = 10 \) and 15 m/s, which span successful and failed suppression, are shown. There is a stagnation zone in the \( z \)-vertical direction since the downwardly injected spray impinges on the upwardly buoyant gas flame. In the stagnation zone, a rollup motion can be observed due to the impingement between spray and gas. In Fig. 3(a), the larger upward motion of the water spray droplet, compared to the motions in Fig. 3(b), is visible because the lower spray momentum is not large enough to overcome the buoyancy force of the fire when \( U_{\text{inj}} = 10 \) m/s. However, suppression was occurring when \( U_{\text{inj}} = 15 \) m/s (note the statistic shown in Fig. 3) is based on \( 80 \leq t < 180 \) sec and complete suppression occurred at about \( t=200 \) sec (see Fig. 2).

As indicated in the comparisons shown in Figs. 2 and 3, the current suppression model is capable of providing not only qualitatively useful insights, but also reasonably acceptable quantitative information.

4. DROP MOMENTUM EFFECT ON SUPPRESSION

In this section, we discuss parametric studies on a large-scale pool fire placed in a 2 m x 2 m square burner at the center of a floor in a 10 m x 10 m x 10 m compartment with an open ceiling, as depicted in Fig. 4. To the authors’ knowledge, scientific fire suppression studies at this large scale have not been conducted, either experimentally or numerically. Figure 4 also shows the coordinate system used in all following discussion.

A direct comparison with experimental data has not been made due to the lack of experimental data for a large-scale compartment fire. It is our presumption that the current numerical code is capable of predicting the correct trends as validated with the experimental data in Section 4. Table 1 lists the parameters covered in this study. It is expected that suppression is achieved for most parametric cases due to the high mass flow rate applied for the water spray system, \( m = 5 \) kg/s. Thus, here we define that the optimum fire suppression condition is found when the selected local flame temperature is reduced to a room temperature of 300 K at the fastest rate with respect to other cases, for a fixed water mass flow rate.

4.1. Computational Details

The water spray is injected from the center of the cube-shaped room, at \( x_{\text{inj}} = y_{\text{inj}} = z_{\text{inj}} = 5.0 \) m, and the droplet velocity was varied from \( U_{\text{inj}} = 20 \) m/s to 80 m/s. The time step used for the gas-phase simulation was \( \Delta t_{\text{gas}} = 0.05 \) sec while the sub-cycling time step for the liquid phase was approximately \( \Delta t_{\text{sub}} = \Delta t_{\text{gas}} / 100 \) sec, set by the stability criterion implemented in the fire suppression code with the given maximum injection speed. A uniformly-spaced grid was applied with a resolution of 132651 nodes (51 x 51 x 51). The cone angle of the spray was set at \( \vartheta = 30^\circ \) and the spray injection was initiated at \( t=20 \) sec. Statistics on the spray characteristics were collected at intervals of 0.002 sec, starting from \( t=25 \) sec through to 30 sec (2500 data points).

The total number of computational parcels injected was 50000 parcels during a 10 sec spray injection duration (or 5000 parcels/sec). The total number of water droplets ranges from 186 million to 12 billion, which yielded an average value of \( 3.72 \times 10^7 \) droplets/parcel. The initial droplet size distribution was assumed to be the Rosin-Rammler distribution shape with the corresponding dispersion coefficient of \( q=3 \), deduced from the measurement obtained for a typical commercial water sprinkler according to Widmann [26].

4.2. Quasi-Steady State of the Hydrocarbon Pool Fire

As indicated earlier, the water spray was initiated at \( t=20 \) sec, when the pool fire reached a quasi-steady state. In Fig. 5, the local gas temperature is shown for various physical locations. The solid and dashed lines correspond to the physical locations \( x=1.7 \) and 5.0 m, respectively, which is off and on the centerline. The legends ‘o’, ‘x’, and ‘*’ represents the vertical locations, \( z=2, 4, \) and 6 m, respectively. As shown, the dashed line data are higher because they were located directly above the pool fire at \( x=5.0 \) m. It is also evident that the location closest to the pool in the vertical direction (i.e., \( x=5 \) m and \( z=2 \) m) has the highest temperature. As the height increases from 2 to 6 m, the temperature decreases above the fire at \( x=5.0 \) m due to increased air entrainment. Away from the fire at \( x=1.7 \) m the opposite trend occurs with the temperature increasing with height, corresponding to the buoyantly stable hot upper layer gases re-circulating in the downward direction as they cool. The stationary room temperatures indicate that the fire has reached a quasi-stationary state prior to the injection of the water spray at 20 s.

From this basic configuration, a parametric study of the
key variables that determine the effectiveness of a water-spray fire suppression system is conducted. These variables include the droplet size and the droplet momentum. These are varied to study the experimental observations that water mist systems, those with small droplet diameters, are extremely effective fire suppression systems if the water mist can get to the fire. The problem arises in getting to the fire because the momentum of the individual droplets is not sufficient to penetrate the fire, the upward buoyant flow tending to push them away. Rather the momentum of the entire spray plays a role in determining the effectiveness when the momentum of the individual drops is not sufficient. These tradeoffs are addressed in the following sections. The issue of the number of nozzles is also addressed. For all of these cases, the fire and the water mass flow rate are held constant. The conditions for the various tests are detailed in Table 1. The results for varying droplet size are presented first, followed by the variations in the spray momentum.  

4.3 Effect of Initial Droplet Size

In Fig. 6, a series of snapshots the water spray, with the droplet injection speed fixed at 20 m/s, is shown for various initial droplet sizes: X=200, 400, and 800 µm (Cases 1, 4, and 7; see Table 1). The smaller droplets decelerate rapidly and are subject to more rapid evaporation, and the smallest droplets from all three of these cases are observed to be lofted upwards by the buoyant fire plume. These droplets do not approach the fire closely enough to effectively suppress the fire. This failure is particularly apparent for case 1 with X=200 µm. Suppression in this case is delayed until the water droplets are re-circulated by the convective flow.

Contour plots for the time-averaged Sauter mean diameter (SMD) are shown in Fig. 7 for X=200, 400, and 800 µm. As in Fig. 7(a), droplets larger than about 500 µm actually landed on the floor (z=0) where the pool fire was located. When the injected droplet size increases, the shape of the spray envelope becomes more apparent as these larger droplets maintain their initial momentum more efficiently. The size distribution for X=800 µm in Fig. 7(c) is such that large droplets (i.e., D ~ 1200 µm, the dark column in the center) were projecting directly in a downward direction while smaller droplets were located between the center column and the edge of the spray envelope. Figure 8 shows the time-averaged radial gas velocities near the pool surface (z=0.25 m) are plotted to show the extent to which the spray momentum is transmitted towards the pool surface. As the spray penetrates the upper regions of the fire a stagnation flow pattern is generated with the radial outflow in Fig. 8. This radial outflow is substantially stronger with the greater initial droplet diameter. In addition to the effectiveness of the droplets in cooling the fire, the stagnation flow can push the fire outward, reducing the view factor between the fire and the pool; this reduces the heat flux to the pool and thus the strength of the fire as also observed by Chow et al [25].

To enhance the effectiveness of smaller droplets, it is hypothesized that increased spray momentum can lead to better mixing of the droplets into the fire. Therefore, the effect of droplet size is also examined for higher initial droplet velocities. These cases, with initial droplet velocities of 80 m/s, and initial mean diameters from X=800 µm to X=100 µm are denoted Cases 9, 6, 3 and 10, in order of decreasing droplet diameter, in Table 1. These results are shown in Fig. 9. Here the greater momentum of the spray enhances the mixing so that the temperature drops off more rapidly that those cases discussed in Figs. 6 and 7. However, the effect of reduced droplet diameter on enhancing the suppression is small. That is, there is a low sensitivity to the droplet diameter at sufficiently high initial velocities. Further, for the smallest (X=100 µm) droplets there is some evidence of marginally higher temperatures with smaller diameters. This implies that the droplet evaporation may be too fast for these large scales, although we suggest that additional work would be required to validate this.

4.4 Effect of Spray Injection Speed

The well-known behavior in which smaller droplets have difficulty suppressing a fire because the individual low momentum droplets are unable to penetrate the buoyant plume was described in the previous section. In the present section, the injection speed is varied to determine the effect of the overall spray momentum in mitigating the above mentioned small-droplet disadvantage.

Figure 10 shows the gas temperature contours at t = 30 sec for various injection speeds, U_{inj}=20, 40, and 80 m/s, under a fixed initial droplet size of X = 400 µm (Cases 4, 5, and 6). For U_{inj}=20 m/s, the maximum gas temperature was around 345 K and thus complete suppression was not achieved. The stagnation zone, where the downward motion of the spray and the upward motion of the buoyant fire met, was slightly below the spray location, z ~ 4.0 m (see Fig. 10(a)). As the injection speed increased, the stagnation zone was pushed downward, to z ~ 1 m for U_{inj}=40 m/s case. Eventually, the zone stopped at z < 1 m for U_{inj}=80 m/s, for the case where complete suppression was achieved. From this observation, we may conclude that the stagnation zone location is a good measure to provide information regarding suppression conditions. As in Fig. 11, the stagnation zone was clearly located near the floor surface, indicative of the strong momentum of spray droplets which overcame the buoyant force of the fire. Certainly, the spray droplet trajectory induced the motion of gas flow, which is similar in motion to the droplet as shown in Figs 11(a) and 11(b).

In Fig. 12, the history of the local gas temperature is shown at various physical locations for Cases 1, 4, and 7, where droplet size was varied. Figure 12 indicates that the largest droplet size resulted in the smallest time to suppression when the injection speed was relatively low (U_{inj}=20 m/s). This pattern was true for all six physical locations as shown in Fig. 12.

5. CONCLUSION

The effect of the average droplet size and the droplet initial velocity in the water-spray suppression of a large-scale JP8 compartment pool fire was studied using the VULCAN suppression model. Comparisons between existing experimental data and the VULCAN predictions showed consistency between the predictions and measurements. A computational study was also conducted to investigate the dependence of the time to suppression on the droplet diameter and initial velocity. This
computational study indicates that higher injection velocities are generally associated with more rapid suppression. This is particularly true for smaller initial droplet diameters that tend to be very effective in suppressing fires if they can be transported into the fire. In this sense, it is observed that an optimal suppression system would operate with small droplets at high initial velocities. For droplet distributions with sufficiently small average diameters, the rate of suppression is relatively insensitive to the droplet size, indicating that additional effort in making smaller or more uniform droplet sizes is unwarranted. For lower initial velocities, however, smaller droplets have trouble penetrating the fire and are relatively ineffective. The location of the stagnation zone between the downwardly injecting spray and the upwardly lifting fire plume was found to be an important parameter for the consideration of the preferred suppression condition.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the Sandia National Laboratories (SNL) under Grant No. LDRD05-0030. SNL is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company for the United States Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000. The second author acknowledges his thanks for financial support provided by Carbon Dioxide Reduction and Sequestration R & D Center (CDRS) and Combustion Engineering Research Center (CERC) of Korea.

6. REFERENCES


Table 1. Parametric case studies conducted during the simulations

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Figure 1. Schematics of the experimental setup of Chow et al [25].

Figure 2. Time evolution of the local gas temperature at $x=1.8$ m, $y=1.2$ m, and $z=0.5$ m (TC1-7 location). Spray injection is initiated at $t=60$ sec and stops at $t=400$ sec.

Figure 3. Time-averaged gas temperature contour at $x=1.8$ m plane. Vectors are plotted using the droplet trajectories. Statistics are collected from $80\,\text{s} < t < 180\,\text{s}$ at the intervals of 1 s for the plots shown in (a) $U_{\text{inj}}=10$ m/s and (b) $U_{\text{inj}}=15$ m/s.

Figure 4. Schematics of the compartment fire of the modeling.

Figure 5. Time evolution of the local gas temperature at various physical locations at the $y=0$ plane. The solid and dashed lines correspond to $x=1.7$ and $x=5.0$ m, respectively. The legends, ‘o’, ‘x’, and ‘*’ represents the vertical locations, $z=2$, 4, and 6 m heights, respectively. A quasi-steady state is reached at about $t=10$ sec. Note that spray injection is initiated at $t=20$ sec and stops at $t=30$ sec.
Figure 6. Time evolution of spray injection at $U_{\text{inj}}=20$ m/s in the x-z axes frame ($y=0$ plane), (first row) $X=200\mu m$, (second row) $X=400\mu m$, and (third row) $X=800\mu m$ (Cases 1, 4, and 7). Small droplets are lifted upwardly due to the buoyancy force of the pool fire while large droplets have enough momentum to penetrate into the fire located at the bottom. The contour color is scaled with the axial velocity of the droplets.

Figure 7. Time-averaged Sauter mean diameter, $D_{32}$, distribution in x-z coordinates ($y=0$ plane) at various injection mean diameters, $X=200\mu m$, $X=400\mu m$, and $X=800\mu m$. Note that the spray injection speed is $U_{\text{inj}}=20$ m/s (i.e., Cases 1, 4, and 7) and the contour level is scaled with $D_{32}$ in the unit of [m].

Figure 8. Time averaged gas radial velocities at near fuel surface (i.e., $z=0.25$ m) for $X=200\mu m$, $X=400\mu m$, and $X=800\mu m$ (i.e., Cases 1, 4, and 7). A stronger radial velocity is shown for larger mean droplet size though droplets were injected at the same speed for all cases.

Figure 9. Comparison of the time history of the local gas temperature for Case 9, 6, 3 and 10 ($X=800\mu m$, $400\mu m$ 200$\mu m$ and $X=100\mu m$) under the spray injection speed, $U_{\text{inj}}=80$ m/s.

Figure 10. Effect of varying the injection speed on the induced local gas velocities and on the suppression mechanism; the suppression is enhanced as the injection speed increases. Contour color is scaled with the local gas temperature in Kelvin unit at t=30 s. Note that the initial mean droplet size is $X=400\mu m$ (i.e., Cases 4, 5, and 6).
Figure 11. Time averaged (a) induced gas and (b) injected droplet velocities for Case 3, X=200 µm and U_{inj}=80 m/s. Vortex rollup is shown near the floor surface (i.e., z = 0); the induced gas is radially convected. Contour color is scaled with the radial velocities of (a) gas and (b) droplet in the units of [m/s]. Note that the vectors are plotted at uniform length for clarity of the presentation.

Figure 12. Comparison of the time history of the local gas temperature for Cases 1, 4, and 7 under the spray injection speed, U_{inj}=20 m/s. Note that the range of the gas temperature for the left panes (x=1.7 m) is up to 420 K, while that for the right panes (x=5.0 m) is up to 1000 K.