Using mixed gases for massive gas injection disruption mitigation on Alcator C-Mod

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Abstract

Mixed gases are used for massive gas injection disruption mitigation on Alcator C-Mod in order to optimize radiation efficiency, halo current reduction and response time. Gas mixtures of helium and argon (argon fraction 0–50\%) are investigated in detail, as well as mixtures of deuterium, argon, krypton and helium. Experiments show that injecting He/Ar mixtures leads to faster thermal and current quenches than with pure helium or argon injection, thus improving the time response of the disruption mitigation system and reducing the halo current. Small fractions of argon (\textasciitilde 5–10\%) in helium also lead to optimized radiation fractions with large electron density increases in the core plasma. These results are consistent with the expectation that small fractions of argon will be entrained with the faster helium in the early phases of gas flow. The gas mixing allows one to simultaneously exploit the fast particle delivery rate of light helium gas and the large radiation capability of argon.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

In a tokamak, disruptions are the sudden loss of energy confinement caused by the destruction of magnetic surfaces. The sudden increase in plasma resistivity associated with the rapidly falling temperature results in a fast current decay and dissipation of the plasma’s thermal and poloidal magnetic energy. Disruptions have deleterious effects through intense localized heat flux to plasma facing components, generation of halo current in the conducting vessel, and the generation of significant current carried in multi-MeV runaway electrons that are eventually lost into plasma facing components. Preventing or mitigating their occurrence will be a requirement for any reactor-regime tokamak [1].

The principle of massive gas injection (MGI) disruption mitigation is to force a rapid and comparatively benign release of the plasma energy through a forced injection of a radiative species into the plasma [2]. MGIs also have the potential to prevent runaway electron formation by creating a strong collisional drag force [3], induced MHD stochasticity [4, 5], and strong bremsstrahlung and synchrotron radiation drag [6]. Because the in-vessel components are often at elevated temperatures, noble gas species, with their low chemical reactivity, are used in MGI experiments.

The location of the gas reservoir and fast valve is an important design consideration for MGI systems. For maintenance access and to avoid radiation damage, it is likely that the reservoir and valve for a burning plasma experiment such as ITER will be located outside the neutron shielding and toroidal field coil set, 3–5 m from the plasma edge. This raises concerns about the overall response time of the mitigation system. A signal can be immediately sent to open the disruption mitigation valve when triggered by a disruption detection system, but the delivery of the radiative species to the plasma is delayed by the time it takes the gas to travel down the pipe from the valve to the plasma edge.

Therefore, it would appear that light gases such as H\textsubscript{2} or He, with high gas sound speeds, would be favoured since they will propagate the fastest to the plasma edge [7]. However, light, low atomic number (low-\(Z\)) impurities have low radiation rate coefficients due to their full ionization in the plasma, which can reduce the effectiveness of the disruption mitigation [8]. On the other hand, heavy, high-\(Z\) gases have high radiation rate coefficients due to their large number of...
bound electrons, but will move more slowly to the plasma, introducing an undesirable delay to the initiation of plasma cooling [9]. Pure-gas injection experiments on the TEXTOR tokamak [10] indicate that the delivery of pure gases can be modelled by a classical shock-front solution, and that heavier pure gases such as argon do not mix as well with the plasma as light gases such as helium, reducing their efficiency as a mitigation gas.

Previous disruption mitigation experiments on the JT-60U tokamak using a conventional gas injection system (∼100 times smaller injection rate than with MGI systems) showed that gas mixtures of low-Z and high-Z noble gases resulted in larger radiated power and a larger density increment, which helped decrease runaway electron formation [9, 11, 12].

We report here on the use of gas mixtures with the MGI disruption mitigation system on Alcator C-Mod [8]. In section 2 we discuss the requirements for disruption mitigation and discuss the benefits of using gas mixtures. In section 3 we present the results of experiments on C-Mod using a helium/argon mixture, showing that disruption mitigation can be optimized with respect to the argon gas fraction. We also present observations of MGI using mixtures of hydrogen/argon and helium/krypton. In section 4 we interpret the observations using a zero-dimensional radiation/ionization code in order to illuminate some of the physics behind the experimental results. Conclusions are given in section 5.

2. Requirements for disruption mitigation

For a disruption mitigation system to qualify as successful, the following three requirements must be met:

- The fast delivery of a large quantity of radiative species into the plasma. The delivery time must be faster than the growth time of the plasma instabilities that lead to the disruption through violation of the tokamak’s operational limits (e.g. vertical displacement, locked-mode, pressure limit, etc)
- Efficient energy removal and density increase before and during the thermal quench (TQ), in order to minimize localized heat loads on plasma facing components, and to prevent runaway electron formation during the current quench.
- Sufficiently rapid and resistive termination of the toroidal plasma current, in order to minimize halo currents. Too rapid plasma current decay, however, leads to large eddy currents and associated $J \times B$ forces on vessel structures [1]. Thus, a successful disruption mitigation system must be able to meet the other goals (fast delivery, efficient energy removal and density increase) while causing a slow enough plasma current decay that eddy forces are acceptable.

In the following subsections, the details of these requirements are discussed.

2.1. Gas delivery

For a given MGI system (plenum, valve, pipe), the delivery rate of the gas to the plasma is set by the gas sound speed. The speed of sound in a monatomic gas at a given temperature depends on the atomic mass $M$ of the gas ($c_s \sim 1/M^{1/2}$). A summary of C-Mod disruption mitigation experiments using pure helium and argon gases [8] is shown in figure 1. Figure 1(a) indicates the effect of gas delivery speeds.

In C-Mod experiments the gas valve is located 2 m from the plasma edge. The gas travels through a stainless steel tube with 9.4 mm internal diameter (13.0 mm external diameter). The effective time response, which is desired to be as short as possible, is defined as the time between the valve opening, $t_{valve}$ (as indicated by the start of the rise of the pressure waveform just downpipe from the valve), and the time of the beginning of the current quench, $t_{CQ}$ (as indicated by the peak in the plasma current measured by a Rogowski coil sampled at 10 kHz). The peak and subsequent decay in the plasma current indicates that the plasma has become cold and highly resistive. The overall response time for pure He injection is found to be ∼25% better than for pure Ar injection. However, this relative advantage for He is far less than the ratio of sound speeds; $c_s$ in He is approximately 3 times faster than in Ar. This indicates a competition between radiation efficiency and the speed of sound in the different gases. We now examine how we can exploit this competition using mixed gases for disruption mitigation.

The particle delivery rate for pure gases can be assessed using a simple analytic model based on Euler’s equation for adiabatic expansion without friction. We assume an infinitely large plenum located at $x = 0$. A fast valve located at $x = 0$ connects the plenum to a constant-diameter pipe which runs from $x = 0$ to $x = L_p$, where $L_p$ is the length of the pipe (m). At $x = L_p$, the pipe empties into a vacuum region of infinite

Figure 1. Summary of pure He and Ar gas jet disruption mitigation experiments on Alcator C-Mod [8]. (a) Time delay from signal being sent to fast valve to beginning of current quench. (b) total radiated energy during entire mitigated disruption, (c) maximum rate of change of plasma current, (d) electron density $n_e$ at beginning of current quench. Note $n_e$ for helium MGI is at detection limits. Neither He nor Ar can fulfill all disruption mitigation requirements.

Parameter $x$ is made infinite in order to not affect the results of the calculations.

2.2. Hydrogen and Argon MGI

For the following calculations we assume $M = 2.0$ amu for $H_2$, $M = 39.95$ amu for $Ar$, and $c_s = 1350$ m/s for both gases. We assume an infinitely large plenum at $x = 0$ connected to a constant-diameter pipe which runs from $x = 0$ to $x = L_p$ where $L_p$ is the length of the pipe (m). At $x = L_p$, the pipe empties into a vacuum region of infinite dimension.

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2.3. Helium and Argon MGI

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Parameter $x$ is made infinite in order to not affect the results of the calculations.

2.4. Mixed Gas Delivery

For mixed gas delivery, we assume that the gas is delivered at a rate $J$ and that the gas travels through a pipe of length $L_p$. The effective time response, $t_{eff}$, is defined as the time between the valve opening, $t_{valve}$, and the time of the beginning of the current quench, $t_{CQ}$, which is indicated by the peak in the plasma current measured by a Rogowski coil sampled at 10 kHz. The peak and subsequent decay in the plasma current indicates that the plasma has become cold and highly resistive. The overall response time for mixed gas injection is found to be ∼25% better than for pure Ar injection. However, this relative advantage for He is far less than the ratio of sound speeds; $c_s$ in He is approximately 3 times faster than in Ar. This indicates a competition between radiation efficiency and the speed of sound in the different gases. We now examine how we can exploit this competition using mixed gases for disruption mitigation.

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Parameter $x$ is made infinite in order to not affect the results of the calculations.

2.5. Summary

In summary, mixed gas injection experiments on Alcator C-Mod [8] indicate that the delivery of mixed gases can be optimized with respect to the argon gas fraction. We also present observations of MGI using mixtures of hydrogen/argon and helium/krypton. In section 4 we interpret the observations using a zero-dimensional radiation/ionization code in order to illuminate some of the physics behind the experimental results. Conclusions are given in section 5.

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Parameter $x$ is made infinite in order to not affect the results of the calculations.
The sound speed of the gas in the plenum is given by

\[ c_0 = \sqrt{\frac{\gamma P_0}{\rho_0}} = \sqrt{\gamma R T_0} \]  

(1)

where \( c \) is the sound speed (m s\(^{-1}\)), \( \gamma \) is the ratio of specific heats, or adiabatic constant, \( P \) is the gas pressure (Pa), \( \rho \) is the mass density of the gas (kg m\(^{-3}\)), \( R = R/M \) is the specific gas constant (J kg\(^{-1}\) K\(^{-1}\)) and \( T \) is the gas temperature (K). The subscript 0 indicates the stagnation condition, assumed to be valid in the plenum where the velocity of the gas is always small.

If the valve opens at \( t = 0 \), the gas flows into the pipe (initially a vacuum), and a shock front develops. The sound speed and fluid velocity \( u \) as a function of \( x \) (distance down the pipe) and time \( t \) are given by [13]

\[ c = \frac{2}{\gamma + 1} c_0 - \frac{\gamma - 1}{\gamma + 1} \frac{L}{c_0} \]

(2)

\[ u = \frac{2}{\gamma + 1} c_0 + \frac{2}{\gamma + 1} \frac{x}{t}. \]

(3)

Examination of (2) shows that at the pipe exit, \( x = L_p \), the solution is physical \((c > 0)\) only after a minimum elapsed time of

\[ \Delta t_0 \geq \frac{\gamma - 1}{2} \frac{L_p}{c_0}. \]

(4)

For an ideal monatomic gas, \( \gamma = 5/3 \). Thus, for noble gases, the minimum delay for gas particles to arrive is \( \Delta t_0 = L_p/3c_0 \). The gas particle delivery rate into the infinite vacuum at \( x = L_p \) is given by

\[ \left. \frac{\dot{N}}{x = L_p} = (n)_{x = L_p} A = \left( \frac{\rho}{M} \right) u \right|_{x = L_p} \]

(5)

where \( \dot{N} \) is the particle delivery rate (s\(^{-1}\)), \( n \) is the particle density (m\(^{-3}\)) and \( A \) is the cross-sectional area of the pipe (m\(^2\)). The gas density \((n \sim \rho)\) is obtained from the adiabatic relationships:

\[ \frac{c}{c_0} = \left( \frac{T}{T_0} \right)^{\frac{\gamma - 1}{\gamma}} = \left( \frac{P}{P_0} \right)^{\frac{\gamma - 1}{\gamma}}. \]

(6)

Thus for \( \Delta t_0 \), we can combine (2), (3), (5) and (6) to determine the particle delivery rate [14]. Normalized to the reservoir conditions, this is given for monatomic ideal gases by

\[ \frac{(n)_{x = L_p}}{n_0 c_0} = \frac{3}{256} \left( 1 + \frac{1}{\gamma} \right) \left( 3 - \frac{1}{\gamma} \right)^3 \]

(7)

where \( t^* = (c_0/L_p) \) is the normalized time, and \((n)_{x = L_p} \times A \) gives the rate of delivery of gas particles into the vacuum at \( x = L_p \).

For fixed hardware \((A, L_p \) constant) and fixed reservoir gas pressure \((n_0 \) constant), the particle delivery rate depends only on the gas sound speed at stagnation \( c_0 \). The normalized particle delivery rate given by (7) as well as the pipe exit velocity and pressure normalized to the plenum conditions are shown graphically in figure 2. It can be seen that the particle delivery rate approaches its steady-state value much more quickly than the pipe exit pressure during the early part of the injection \((t^* \lesssim 1.5)\). For example, the particle delivery rate is \(\sim 60\%\) of its steady-state value after one sonic transit time \((t = L_p/c_0)\), while the pressure has only reached \(\sim 13\%\) of its steady-state value. This is significant because pipe exit pressure is typically used as the (indirect) indicator of gas flow in gas jet mitigation experiments [15].

Taking the C-Mod case of \( L_p = 2 \) m, the sonic transit times \( L_p/c_0 \) for helium \((c_0 \simeq 1000 \) m s\(^{-1}\)) and argon \((c_0 \simeq 320 \) m s\(^{-1}\)) are 2 ms and 6 ms, respectively. Given that the characteristic timescale for C-Mod disruption quenches is 1–2 ms, the importance of prompt gas delivery is obvious. In particular, it is important to realize that it is the initial delivery of gas \((t = L_p/c_0)\) that initiates the sequence leading to radiative termination (TQ). However, for the case of argon, the ‘bulk’ of the gas is not delivered until more than 4 ms after this time. This is obviously undesirable with respect to maximizing the delivered particle inventory in the current quench.

However, this limitation for argon delivery can be overcome by noting that the gas in the pipe is in a strongly viscous regime (Knudsen number \( Kn \ll 1 \)) and thus the components will not separate [16]. Therefore, for nonreacting mixtures of noble gases such as argon mixed with helium, for the purposes of calculating the sound speed, the mixture can be treated as a single species with an effective atomic mass set by the admixture concentration of Ar in He. In the case of a small concentration of argon mixed with helium \((f_{Ar} \lesssim 10\%\)), the argon atoms are efficiently entrained with the helium and are delivered at a much faster rate than is possible with pure Ar gas. The rapid delivery of the highly radiating argon brings advantages that will be explained in the following sections.

2.2 Energy removal

Although the fast delivery of species into the plasma is critical to mitigate the disruption, it is not enough by itself. The injected species must be effective at radiating away the plasma energy to prevent localized heat flux, and increase the total electron density (including both free and bound electrons; see section 3.2) at the same time to prevent runaway formation.
It has been shown [8] that high-Z impurities, having large radiation rate coefficients, can radiate the energy of the plasma efficiently. This is true even when they are injected in low quantities, as with killer pellets [17] or low-pressure gas puffing [11]. As a result, the radiative fraction of the stored energy is higher with argon than with helium, as can be seen in figure 1(b). In these experiments, the gas jet was fired into plasmas with total plasma energy \( W_{\text{th}} + W_{\text{mag}} \lesssim 0.65-0.8\,\text{MJ} \). The fraction of total plasma energy radiated is thus approximately 30–40% for He and 75% for Ar, a clear improvement from unmitigated disruptions which typically have a radiated energy fraction of 20–30%. However, because of their slower particle delivery rate, high-Z impurities do not increase the electron density as effectively as He does. A high electron density is desirable for runaway suppression. A summary of density increments before the current quench with different noble gases is shown in figure 1(d). The highest density increments are obtained with helium; however, due to the low radiation rate of pure He, these injections are not as successful at mitigating the localized heat flux by radiative dissipation [8, 9].

If a mixture of mostly low-Z gas with small concentrations of high-Z gas can be delivered quickly to the plasma, it may remove the energy quickly and trigger the current quench earlier. The radiation power \( P_{\text{rad}} \) of a plasma contaminated with an impurity is approximately given by \( P_{\text{rad}} = n_{e}n_{Z}L_{c} \), where \( n_{e} \) and \( n_{Z} \) are the number density (m\(^{-3}\)) of free electrons and impurity atoms, respectively, and \( L_{c} \) is the radiation rate coefficient (W m\(^{-3}\)) for the impurity. Thus, injecting a mixture can lead to large radiation power densities even if the specific radiation rate coefficient of the high-Z mixture is low, because the ionization of the low-Z gas contributes many free electrons. One obtains a double benefit with the gas mixture: the high-Z impurities arrive more quickly due to their viscous transport by the low-Z carrier gas, and the efficiency of the radiation is improved by the electrons contributed by the ionization of the carrier gas.

2.3. Resistive termination

After the TQ, poloidal halo currents become a concern. These can be decreased by increasing the current quench rate [18]. After the TQ, the plasma temperature and hence resistivity are determined primarily by the the ionization energy of the injected gas, as can be seen in figure 1(c). This is because the plasma is in equilibrium between ohmic heating and line radiation [3]. In the case of mixed gas species, the temperature will primarily be set by the species with the lowest ionization temperature, since that species will continue to radiate until the plasma has reached a temperature low enough to come into balance between ohmic heating and radiation for that species (see figure 2 of [3]). In the case of helium–argon mixtures, then, it is expected that Ar (ionization energy 16 eV) will dominate over He (ionization energy 24 eV). This holds even if the argon is a small fraction of the helium, due to the exponential sensitivity of ionization rate to temperature when the temperature is below the ionization energy. The current quench rate is then proportional to the resistance and inversely proportional to the plasma inductance. The internal inductance typically falls from its pre-disruption value to approximately \( \frac{1}{2} \) as the current profile flattens at the end of the TQ [19]; it then remains near this value through the current quench, and thus it is primarily the resistance that sets the current quench rate. We therefore expect the gas mixture to cause a reduction in halo current, similar to that found with pure argon, even at low admixture fractions.

3. Experimental setup and observations

The gas jet disruption mitigation system on Alcator C-Mod consists of a 300 mL high-pressure plenum that is typically filled to 7 MPa with a noble gas. A fast-response valve, located at the plenum, delivers the gas into a connecting pipe of 2 m length, and 9.4 mm internal diameter. The valve is open for approximately 1.3–2.0 ms. Technical details of the disruption mitigation system are presented in [8]. Disruption mitigation experiments using mixed gases were performed during four runs in 2006, 2007 and 2009.

The 2006 experiments began with pure He injection on the first shot. Then, after each shot, the plenum was refilled in situ using a 50%He + 50%Ar gas mixture. This gradually increased the Ar fraction of the plenum, allowing us to do a scan of Ar concentrations in a single run. The actual fractions of species were measured using a residual gas analyser. The main target plasma parameters were \( I_{p} = 1.2\,\text{MA}, n_{e0} \sim 10^{20}\,\text{m}^{-3} \), and \( B_{t} = 5.4\,\text{T} \). Further experiments were performed in 2007 and 2009 using an 85%He + 15%Ar gas mixture as well as mixtures of 85%D\(_{2}\) + 15%Ar and 85%He + 15%Kr into a target plasma with \( I_{p} = 1.0\,\text{MA}, n_{e0} \sim 10^{20}\,\text{m}^{-3} \) and \( B_{t} = 5.5\,\text{T} \).

In figure 3 we show waveforms of the electronic trigger to the valve, the pressure rise at the pipe inlet (just downstream from the high-pressure plenum), the central soft x-ray signal from the plasma, and plasma current for a typical disruption mitigation experiment using a mixture of 88%He + 12%Ar. The valve opens, indicated by the rising pressure ~2 ms.
Observations are all consistent with expectations for low-Z gas admixtures. The mixed gas mixture is smallest with the 90%He + 10%Ar mixture. These overlaps with that of pure He. Poloidal halo currents with the mixture at the early phase of injection nearly the current decays more rapidly than with pure He, indicating digitization rate of the plasma current Rogowski coil) and uncertainty of approximately 0.5 ms.

The timing of the plasma current resistively decays. The timing of this sequence is highly reproducible (variation < 0.1 ms) if the target plasma and injection gas type and pressure are kept constant.

Waveforms of edge soft x-ray intensity, plasma current, poloidal halo current, and line-integrated electron density for for disruption mitigations using pure helium (blue circle), a mixture of 90%He + 10%Ar (red square), and a mix of 50%He + 50%Ar (green triangle).

3.1. Gas delivery speed
The time of the cooling of the plasma edge (indicated by the delay between the start of the pressure rise at the valve and the collapse of the edge soft x-ray signal on SXR chords 5, 6 and 7, at \( r/a = 0.96, 0.91 \) and 0.87, respectively) is plotted versus the sound speed for several gas mixtures in figure 5. Also shown is the signal from when radiation was first observed on a fast ultraviolet diode pointing at the gas jet [20, 21]. It can be seen that the gas arrives at the plasma at a time very close to the predicted time \( \Delta t_0 = L_p/c_0 \), but that the edge soft x-ray collapse is delayed due to the time it takes the injected impurities to radiate away the energy in the outer layers of the plasma. The mixture of 15%Ar + 85%D2 used in one set of MGI experiments has a specific heat ratio \( \gamma \simeq 1.44 \) and thus the shock arrives after a delay \( \Delta t_0 \simeq 0.22L_p/c_0 = 0.7 \) ms. This is indicated by a dashed line.

3.2. TQ and radiation power
As discussed in section 2.2, the ability of the gas to effectively radiate the plasma energy away during the TQ is critical to prevent localized heat loads to plasma facing components. The time-integrated radiation power (measured using a foil bolometer with a wide-angle view of the plasma; see [8, 22] for details) through the entire mitigated disruption versus the argon fraction for a series of Ar/He disruption mitigation shots is shown in figure 7(a). As expected, the lowest radiated energy is seen for pure helium. The radiated fraction of the total energy
Figure 6. The time of the collapse of the edge soft x-ray signals correlates with the time of the arrival of the gas to the plasma for argon/helium mixtures. Blue circles: chord 5 \((r/a = 0.96)\), green squares: chord 6 \((r/a = 0.91)\), red triangles: chord 7 \((r/a = 0.87)\). A fast photodiode pointing directly at the gas jet [20] indicates the arrival of the gas at the plasma. Dashed lines indicate the modelled gas arrival time \(L_p/3c_0\) and the sonic transit time \(L_p/c_0\).

Figure 7. Radiated energy during mitigated disruption (as measured with a wide-angle foil bolometer and delay time from valve signal to start of current quench, for mixtures of argon/helium. (a) For argon fractions less than approximately 20%, the radiated energy increases with the argon fraction. (b) The delay to the start of the current quench is a minimum for argon fractions of approximately 10–15%.

Figure 8. (a) Helium/argon mixtures with low argon fractions produce the maximum current quench rates. (b) The L/R current-decay timescale (estimated from an exponential fit to the plasma current during the current quench) in all Ar/He mixtures is lower than that in pure helium, and consequently the peak halo current (c) is lower using gas mixtures.

resolution to distinguish between the energy radiated during the TQ and during the current quench. It is clear, however, that on Alcator C-Mod, where TQ and CQ time scales are similar (both are of order 1 ms in duration), that low admixtures of argon are sufficient to obtain a high radiated energy fraction during gas jet mitigated disruptions.

In figure 7(b), the time elapsed from the triggering signal being sent to the disruption mitigation valve to the start of the current quench (defined as the maximum measured plasma current) is shown for the same series of Ar/He discharges. This delay time reaches a minimum for argon fractions of 10–15%. This demonstrates the advantages of gas mixtures: high radiation efficiency with a fast global response time.

The density increment before the current quench is particularly important for runaway electron suppression. The free electron density measured during 3 disruption mitigation experiments using He/Ar mixtures in C-Mod is shown in figure 4(d). These density rises are reproducible and the three cases shown should be considered representative. The highest density increment is obtained with pure helium and the lowest with the 50%He + 50%Ar mixture. These signals show the free electron density in the plasma. However, for runaway electron suppression, it is the total electron density \(n_e,T\) (including bound electrons) that is significant. The total electron density (including bound electrons) was not measured in these experiments, and therefore we have investigated \(n_e,T\) using the KPRAD 0D transport code in section 4.2.

3.3. Current quench and resistivity

The halo currents measured during the experiments are shown in figure 8(c) for helium/argon gas mixtures. The highest halo current is observed during pure He injections, although this is

increases with the fraction of argon in the mixture, up to an argon fraction of approximately 10%. For larger fractions, the radiation fraction is nearly constant.

In all of these shots, the plasma thermal energy is approximately 125 kJ, and the total stored energy available to the disruption (plasma thermal energy + poloidal magnetic field energy) is approximately 650 kJ. It should be noted that the bolometer measurement does not have sufficient time
still an improvement from unmitigated VDE disruptions with $I_{halo} \sim 225$ kA. This is consistent with previous experimental observations [8]. All mixtures lead to lower halo current than with pure He. However, there is little additional reduction in halo current for argon fractions above 10%. Likewise, it can be seen in figures 8(a) and (b) that the current quench proceeds faster (the plasma has been forced to a more highly resistive phase) for argon fractions up to approximately 10%, but there is little improvement above this. This is consistent with the physical picture presented in section 2.2—the argon dominates the thermal balance of the CQ plasma even at low admixture fractions.

4. Discussion

We have used a simple 0D transport code with energy balance (KPRAD) to calculate the response of a plasma with similar experimental parameters to the target plasmas used in the disruption mitigation experiments. Originally written for the simulation of killer pellet injection into plasmas, KPRAD self-consistently calculates the time-dependent electron and ion temperatures, electron density and charge state densities of all impurity and main ion species in a simple zero-dimensional plasma simulation with line radiation and ohmic heating, in order to gain insight into the role of different species during the TQ of a gas jet mitigated disruption. The dynamics of the inward-moving cooling front are not treated by the zero-dimensional KPRAD simulations. For further details on KPRAD, see [23]. The flow rate of the injected species in the simulations is obtained from the analytical equations given in section 2.1. There are no free parameters in the simulations.

4.1. Gas delivery speed

In section 3.1 we used the soft x-ray signals at the edge (chords 5–7) as an indication of the time when the edge plasma had cooled—that is, when the radiation power from the injected gas species has become much higher in the edge region than the sources (ohmic and transport from the core) in this region. A fast photodiode looking directly at the gas jet showed that the actual arrival of the gas at the plasma was described well by the analytic model presented in section 2.1.

As can be seen in figure 5, the timing of the soft x-ray collapse correlates with the time when the gas arrives at the plasma, although with a different numerical coefficient ($\Delta t_{SXR} \sim L_p/2c_0$). This difference is likely due to the time required for the gas injection to accumulate to sufficient density in the plasma to cause the edge plasma to suddenly cool. The delay from the arrival of the gas at the plasma to the onset of the TQ is discussed further in [21]. For analysing the flow rate of gas mixtures, equation (7) is adequate.

4.2. TQ and radiation power

In figure 5 it was shown that the edge temperature collapse, which starts the sequence of events leading to the TQ, starts earlier using mixtures with higher sound speeds. The second critical requirement for disruption mitigation is the electron density increment. The free electron density increment gives a qualitative indication of the particle delivery; however, it is the total electron density (free + bound) which must be raised above the Connor–Hastie–Rosenbluth limit [24, 25] for complete suppression of runaway electrons. The results of a 0D simulation are shown in figure 9, with results similar to the experimental results (see figure 4(a)). The simulated free electron density is also consistent with the experimental results (see figure 4(d)). In the case of helium–argon gas mixtures, the contribution of the argon to the density increment is $\sim 20\%$. The free electron density decreases once the simulated (0D) plasma temperature is low enough for recombination to occur. (c) Similar total (free + bound) electron density is obtained using pure He and 90%He + 10%Ar.

![Figure 9. KPRAD simulations of gas injection were conducted, with the gas being introduced into a 2 m pipe at time $t = 0$. (a) The simulated (0D) plasma temperature is consistent with the experimental SXR emission results (see figure 4(a)). (b) The simulated free electron density is also consistent with the experimental results (see figure 4(d)). (c) Similar total (free + bound) electron density is obtained using pure He and 90%He + 10%Ar.](image-url)

4.3. Current quench and resistivity

The KPRAD code [23] was also used to calculate the plasma resistivity immediately after the TQ for simulated injections of helium–argon mixtures. The experimental post-TQ resistivity was calculated from the observed $L/R$ current-decay timescale during the current quench. The plasma inductance was estimated using the value for evenly distributed current density in a ring: $L = \mu_0 R_0 \ln(8 R_0/a) - 7/4$, where $R_0$ and $a$ are the plasma major and minor radii (0.67 m and 0.22 m for C-Mod, respectively). The two are compared in figure 10. It can be seen that the KPRAD simulation agrees with the experimental results; that the post-TQ plasma resistivity is optimized for low argon fractions ($\sim 5–10\%$).
Figure 10. Observed (from current decay $L/R$ timescale) and calculated (KPRAD) resistivity of the plasma immediately after the TQ, for helium–argon mixtures. Using a mixture of approximately 10% Ar forces the plasma to a highly resistive phase.

5. Conclusions

Helium–argon and other gas mixtures were used in disruption mitigation experiments on Alcator C-Mod to investigate the advantages of mixtures versus single-species injections. Through comparison with pure-gas experiments and numerical calculations, the following results have been obtained:

- The speed of gas delivery for a variety of gas mixtures is well described by assuming that the gas mixture is in a highly viscous regime, and acts as a single gas with an effective sound speed set by the effective atomic mass and adiabatic constant for the mixture.

- Helium–argon mixtures with a low argon fraction approach the plasma at speeds much greater than for pure argon. They produce a similar total (free + bound) electron density increment as does pure helium. For complete suppression of runaway electrons (Connor–Hastie–Rosenbluth runaway suppression limit), the total electron density is the critical parameter which must be raised.

- The radiated power fraction using helium–argon mixtures is improved from pure helium injections, and is similar to that using pure argon injections (see [8]). Halo currents are reduced using gas mixtures instead of pure helium.

- Helium–argon mixtures trigger the current quench faster than pure helium or pure argon (see figures 1(a) and 7(b)). The current quench time appears to be optimized at approximately 10% argon in helium.

- Overall, massive gas jet disruption mitigation using argon–helium gas mixtures appears to be optimized at an argon content of approximately 10–15%.

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